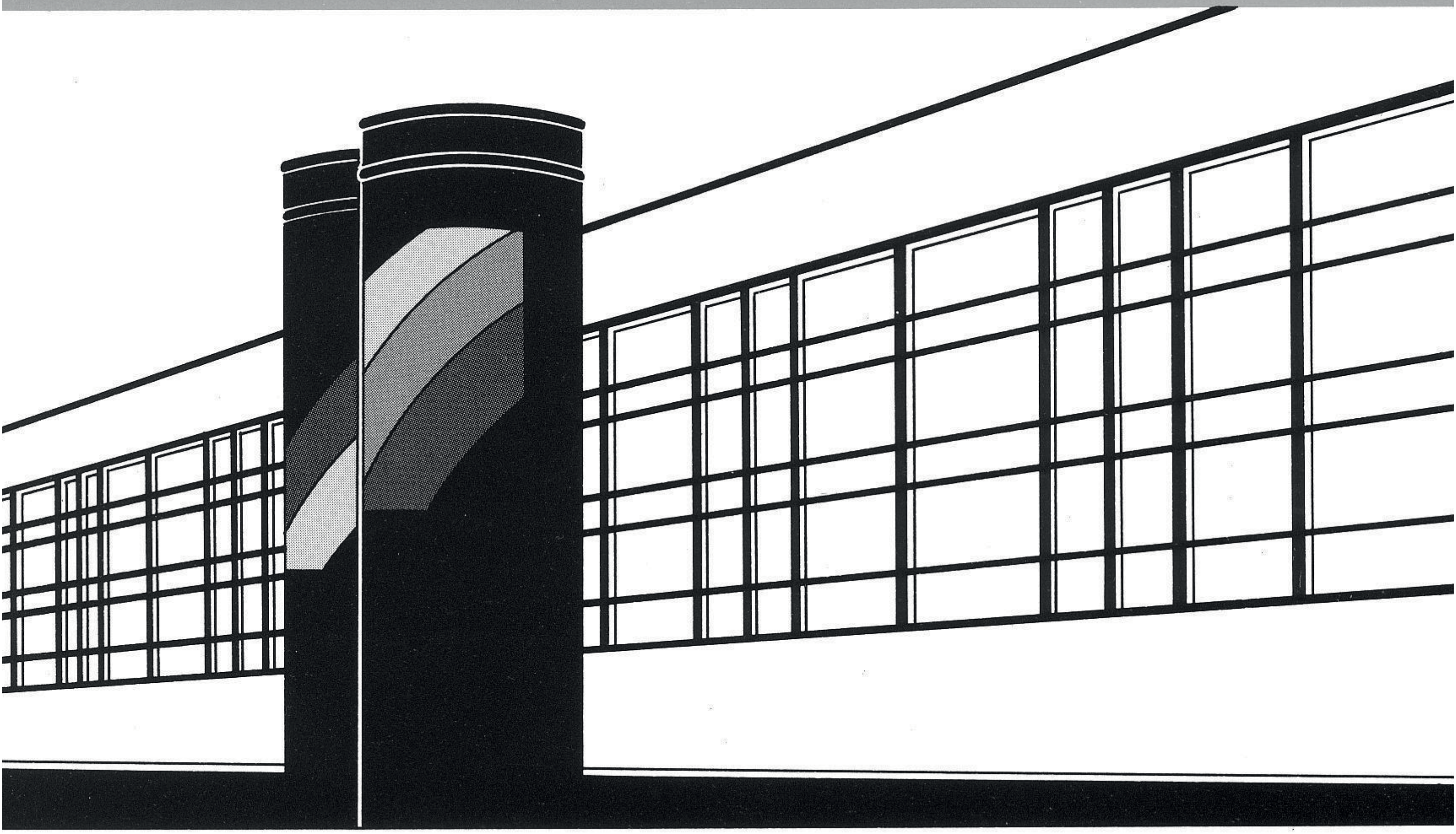
Universität Stuttgart

Institut für Wasser- und Umweltsystemmodellierung

Mitteilungen



Heft 214 Markus Noack

Modelling Approach for Interstitial Sediment Dynamics and Reproduction of Gravel-Spawning Fish

Modelling Approach for Interstitial Sediment Dynamics and Reproduction of Gravel-Spawning Fish

Von der Fakultät Bau- und Umweltingenieurwissenschaften der Universität Stuttgart zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.) genehmigte Abhandlung

Vorgelegt von

Markus Noack

aus Bietigheim-Bissingen

Hauptberichter:	Prof.-Dr.-Ing. Silke Wieprecht
Mitberichter:	Priv.-Doz. Mag. Dr. Gregory Egger

Tag der mündlichen Prüfung: 03. Juli 2012

Institut für Wasser- und Umweltsystemmodellierung
der Universität Stuttgart
2012

Heft 214

Modelling Approach for Interstitial Sediment Dynamics and Reproduction of Gravel-Spawning Fish

von
Dr.-Ing.
Markus Noack

Eigenverlag des Instituts für Wasser- und Umweltsystemmodellierung
der Universität Stuttgart

D93 Modelling Approach for Interstitial Sediment Dynamics and Reproduction of Gravel-Spawning Fish

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://www.d-nb.de abrufbar

Noack, Markus:
Modelling Approach for Interstitial Sediment Dynamics and Reproduction of Gravel-Spawning Fish / von Markus Noack. Institut für Wasser- und Umweltsystemmodellierung, Universität Stuttgart. - Stuttgart: Institut für Wasser- und Umweltsystemmodellierung, 2012

(Mitteilungen Institut für Wasser- und Umweltsystemmodellierung, Universität Stuttgart: H. 214)
Zugl.: Stuttgart, Univ., Diss., 2012
ISBN 978-3-942036-18-4
NE: Institut für Wasser- und Umweltsystemmodellierung <Stuttgart>: Mitteilungen

Herausgegeben 2012 vom Eigenverlag des Instituts für Wasser- und Umwelt-systemmodellierung

Druck: Document Center S. Kästl, Ostfildern

Acknowledgements

First of all, I would like to express my gratitude to Prof. Dr.-Ing. Silke Wieprecht, chair of the Department of Hydraulic Engineering and Water Resources Management and director of the Institute for Modelling Hydraulic and Environmental Systems (IWS) at the University of Stuttgart for supervising this thesis. Without her encouragement, support, and fruitful discussions this thesis would not have been realizable. I greatly enjoyed the years as a research assistant at IWS and I appreciate the opportunities to take part in numerous interesting national and international projects and have enjoyed her company in many places around the world.

Further, special thanks go to Priv.-Doz. Mag. Dr. Gregory Egger, executive director of Umweltbuero GmbH in Austria, as the co-supervisor of my studies. When I first met him on a conference in Chile I was impressed by his dedication to research and unique working style. His everlasting encouragement to invest time in academic education and research is outstanding and an exemplary attitude for everyone.

Very warm thanks go to Johannes Ortlepp and Uta Muerle, who supported me in many ways. Especially Johannes' effort has to be emphasized, for it was him who brought me to the fascinating study site on the River Spoel and supervised the whole thesis from a biological point of view. I benefited not only from his work on this thesis but also from his company and discussions.

I am also very grateful to Prof. Nils Reidar B. Olsen and Dr. Nils Ruether from the Department of Hydraulic and Environmental Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway and Marc Roberts from the German Federal Institute of Hydrology (BfG). Without their support and help I would not be able to use the numerical model SSIIM2 for simulating morphodynamic processes.

I want to express my gratitude to the team of sje Schneider & Jorde Ecological Engineering GmbH. Especially to Dr. Matthias Schneider who introduced me to the fascinating field of ecohydraulic research. I benefited much from his scientific experience and I really enjoyed the years of collaborated research in Stuttgart both, professionally and personally. Further I wish to thank Dr. Ianina Kopecki who always has an open mind for any upcoming problems, especially in terms of technical support with CASiMiR. Lastly, Jeff Tuhtan has to be mentioned as he supported me in many field campaigns and he was always and everywhere (field, office, pub) a pleasant consort.

I am also very grateful to my colleagues at the Institute for Modelling Hydraulic and Environmental Systems for having a pleasurable time in a friendly atmosphere leading to many fruitful discussions. Especially mentioned are the employees of the Hydraulic Laboratory who supported me in providing specific field equipments.

There are many people who worked on corrections of this thesis. Above all, there are to mention Dr. Matthias Schneider, Dr. Ianina Kopecki and Johannes Ortlepp but also Dr. Gudrun Hillebrand, Dr. Frauke Koenig and Dr. Markus Promny. Their rewarding comments and suggestions helped me a lot in finishing this work. The corrections of English were performed by Jeff Tuhtan, John Craven and Nina Mueller. For their invested time I am very grateful.

I would like to thank the people working for the Swiss National Park. In particular, to Dr. Flurin Filli and Dr. Thomas Scheurer who enabled the studies on River Spoel and gave me support for all arising questions and literature. Further, Nicola Gaudenz from the local fish authorities supported me in the biological investigations in the field and provided helpful biological information about the brown trout in River Spoel.

Not to forget numerous students who accompanied the extensive monitoring campaigns. Thanks a lot for the support in field work; especially under extremely harsh conditions.

I also want to say thanks to my family for their unconditional support and it is beyond words to express my gratitude to my wife Nina for everlasting encouragement, patience and love while I indulged myself in this thesis and I am forever indebted to her for that. Finally I want to thank my daughter Leni Anouk and our unborn child for the never known feeling of happiness and deepest satisfaction.

Thank you everyone, I am very grateful.

Markus Noack

Stuttgart, Germany

Table of Contents

List of Figures

List of Tables

Notations

The following symbols are used in this thesis:

A	[m²]	element area
a_{bx},a_{bx}	[-]	cosines for transport direction of bed load
A_F	[m²]	filter area
A_{total}	[m²]	total wetted area
c_A	[-]	Arrhenius constant
c_b	[kg/m³]	bed load concentration
c_i	[-]	coefficients
c_S	[kg/m³]	suspended sediment concentration
$c_{S\delta}$	[kg/m³]	suspended concentration at reference level δ
c_R	[-]	coefficient for the maximum of infiltration resistance
d	[m]	particle diameter
D^*	[-]	dimensionless particle diameter
D_B	[kg/m²s]	deposition rate
d_g	[m]	geometric mean particle diameter
d_i	[m]	upstream particle diameter for hiding/exposure
d_j	[m]	downstream particle diameter for hiding/exposure
d_k	[m]	particle diameter in non-uniform mixtures
d_m	[m]	mean/characteristic particle diameter [-]
$d_{m,D}$	[m]	mean particle diameter of surface layer
$d_{m,i}$	[m]	mean particle diameter of subsurface layer
d_{max}	[m]	maximum particle diameter of surface layer
E_B	[kg/m²s]	entrainment rate
e_s	[-]	calibration coefficient, sediment infiltration (Schaelchli, 1993)
f	[-]	uniform probabilistic function
F_{mk}	[-]	fraction of infiltrated fine sediments relative to total volume
Fr^*	[-]	solid Froude number
F_{Sat}	[-]	fraction of infiltrated fine sediment for saturated river beds
g	[m/s²]	acceleration due to gravity
h	[m]	water depth
h_{inf}	[m]	depth of sediment infiltration
i	[-]	vertical hydraulic gradient
I	[-]	slope
k_p	[m/s]	permeability
k_{p0}	[m/s]	permeability of unsilted riverbed
k_r	[m]	roughness
L	[m]	adaption length for non-equilibrium transport

Ls	[m]	seepage length
m	[-]	calibration coefficient for Wu's hiding/exposure function
m_k	[kg/m²]	sediment infiltration mass
n	[-]	Manning's roughness (bed forms)
n'	[-]	Manning's roughness (grain)
n_d	[-]	number of days
n_p	[-]	porosity
p_b	[-]	percentage of particles in river bed
p_{ei}	[-]	probability of exposed particles of size i
p_{hi}	[-]	probability of hidden particles of size i
p_i	[-]	percentage of fraction i
p_{ML}	[-]	fraction of subsurface layer
p_{SL}	[-]	fraction of surface layer, size
Q	[m³/s]	discharge
q_b	[kg/sm]	bed load transport by mass per unit time and width
q_{b*}	[kg/sm]	equilibrium bed load transport
q_S	[kg/sm²]	vertical sediment flux
r	[-]	Rouse number
Re^*	[-]	solid Reynolds number
Re	[-]	Reynolds number
$R_{H,A}$	[gO_2/m²d]	aerial hyporheic respiration rate
$R_{H,V}$	[gO_2/m³d]	volumetric hyporheic respiration
r_s	[m/kg]	specific infiltration resistance
$S_{f,j}$	[-]	exchange between surface and subsurface layer
$S_{x,y}$	[kg/sm]	total transport rate in x- and y-direction
t	[s]	time
T_I	[°C]	interstitial temperature
$T_{R,H}$	[°C]	interstitial reference temperature
T_W	[°C]	water temperature
$u_{x,y,z}$	[m/s]	flow velocity in x-, y-, z-direction
v_{cr}	[m/s]	critical velocity for incipient motion
V_S	[m³]	seepage water volume
z_S	[m]	sediment concentration level
Δe	[-]	exposure height [m] for hiding/exposure correction
Δp_S	[N/m²]	pressure difference

The following Greek symbols are used in this thesis:

α	[1/m]	infiltration resistance induced by deposited fines
β	[1/m]	infiltration resistance of unsilted river bed
β_0	[-]	trapping coefficient for sediment infiltration, Cui (2008)
δ	[m]	reference level for suspended concentration
δ_{ML}	[m]	thickness of subsurface layer
δ_{SL}	[m]	thickness of surface layer
ε	[m²/s]	sediment diffusion coefficient
θ_{cr}	[-]	dimensionless critical Shields number
κ	[-]	Karman constant
μ	[kg/ms]	dynamic viscosity
ν	[m²/s]	kinematic viscosity
ρ_S	[kg/m³]	density of sediments
ρ_W	[kg/m³]	density of water
σ	[m]	standard deviation
σ_g	[m]	geometric standard deviation
τ_B	[N/m²]	bed shear stress
τ_{cr}	[N/m²]	critical shear stress
Φ	[-]	dimensionless transport intensity
Φ_b	[m³/sm]	bed load transport by volume per unit time and width
Φ_c	[-]	calibration factor for sediment infiltration, Cui (2008)
ω_s	[m/s]	settling velocity

Abbreviations

The following abbreviations are used in this thesis:

ANN	artificial neural network
ATU	accumulated thermal units
BOD	biological oxygen demand
BS 1-6	bulk sediment samples
CASiMiR	Computer Aided Simulation Model for Instream Flow Riparia
CSI	composite suitability index
COD	chemical oxygen demand
DO	dissolved oxygen
DOC	dissolved organic concentration
ETF	egg-to-fry-survival
FI	Fredle-Index
FC 1-6	freeze-core samples
GLM	general linear model
HHS	hydraulic habitat index
HSI	habitat suitability index
IBM	individual based model
IHS	interstitial habitat suitability
LR	logistic regression
MLR	multiple linear regression
POC	particulate organic concentration
R1-9	artificial redd 1-9
RANS	Reynolds-averaged Navier-Stokes equations
RHS	reproduction habitat suitability
SO	sorting coefficient
SOD	sediment oxygen demand
SP 1-3	spawning area 1-3
SSI	spawning sediment index
SSIIM	Sediment Simulation in Intakes with Multiblock option
WFD	EU Water Framework Directive 2000/60/EC
WUA	weighted usable area

Abstract

The complexity and dynamic nature of ecosystem processes impose high requirements on the approaches, methods and modelling techniques applied to support ecological assessments of rivers. Particularly the interactions of abiotic and biotic variables, the high spatial and temporal variability of parameters and processes and the interdisciplinary research field present a special challenge on the development of appropriate tools. Given the naturally dynamic creation, destruction and maintenance of habitat templates in rivers (habitat dynamics) the habitat can be regarded as a basic element of fluvial ecosystems. Accordingly, high demands are placed on aquatic habitat modelling techniques emphasizing the need for the improvement and further development of existing approaches.

The present study predominantly addresses three research fields encompassing the hydromorphology, the fluvial ecology and the hyporheic interstitial of rivers. All disciplines are involved by interacting processes defining the quality of reproduction habitats for gravel-spawning fish. This work is focused on implementing the hydromorphological and hyporheic variability in physical habitat modelling considering all variables that describe the habitat in their spatial and temporal variability to allow a dynamic representation of habitat suitability. Therefore a sophisticated 3D-numerical model to simulate the hydromorphological variability in combination with additional habitat variables that describe the hyporheic variability is applied to obtain detailed information about the abiotic habitat characteristics during the reproduction period which provide the basis for simulating habitat dynamics. The reproduction period of gravel-spawning fish works as an excellent indicator for habitat dynamics, as the life-stages during reproduction (spawning, incubation, and emergence) are not only characterised by high requirements but also by different requirements on the habitat. Based on the abiotic description of the environment a multi-step habitat modelling framework is developed that addresses each life-stage during the reproduction by an appropriate selection of key habitat variables that are linked via a multivariate fuzzy-logic model to simulate habitat suitability indices of each life stage during the reproduction period. The last step of the modelling framework includes the aggregation of the dynamic habitat values to a temporally integrated parameter and the final result of the modelling framework, the reproduction habitat suitability.

The proposed multi-step habitat modelling framework is applied in a mountainous river reach downstream of a dam. The hydromorphological variability arise on the one hand from artificial floods inducing bed level changes and particle sorting processes and on the other hand from infiltration processes of fine sediments during the regulated low flow period causing an accumulation of fine material in the interstitials of the gravel river bed. Both hydromorphological aspects and their corresponding effects on sediment characteristics are successfully reproduced by the 3D-numerical modelling tool. However, restrictions are made regarding the exact reproduction of bed deformations invoked by artificial flooding and the required simplifications for sediment infiltration in order for the model to function. Further, special care must be taken with regards to the applied formulas, empirical values and calibration factors affecting the numerical results.

The hyporheic variability is addressed by linking key habitat factors describing the interstitial habitat suitability for reproduction of gravel-spawning fish species via a multivariate fuzzy-logic approach. Therefore the permeability is used to describe the capability of sediment characteristics to transport oxygen-rich surface water and metabolic waste products. The interstitial temperatures are applied to indicate the metabolic activity and defining upper and lower lethal and sub lethal limits, while the hyporheic respiration is used as a key factor to describe the oxygen demand of biogeochemical processes. Linking these key factors to

spatially and temporally varying values of interstitial habitat suitability for different life-stages during the incubation period of gravel-spawning fish (eyed-egg, hatching, larvae) produced reliable results. Particularly the impact of short-term effects on habitat quality like critical temperatures and the impact due to long-term effects like a continuously decreasing permeability could dynamically be determined. However, improvements regarding the implementation of a proper description of hyporheic exchange processes between groundwater and surface water (up- and downwelling processes) would be beneficial for this fuzzy-approach.

For the multi-step habitat modelling framework to simulate the habitat dynamics of all life-stages during the reproduction period of gravel-spawning fish the spatial and temporal variations of key habitat variables and habitat requirements are identified and linked by multivariate fuzzy-modelling to life-stage specific habitat suitability indices. For the spawning habitat totally six habitat variables are applied. While the fractions sand, gravel, pebbles and cobbles are used to describe the sediment characteristics, the hydraulic characteristics are represented by the variables water depth and flow velocity. Regarding the incubation habitat the interstitial habitat suitability is combined with the bed level changes and the direction of the vertical hydraulic gradient to consider the possible erodibility of buried eggs and larvae as well as the identification of upwelling processes that prevent the oxygen supply to eggs and larvae. The emergence habitat is described by the geometric mean particle diameter, the amounts of particles less than 8 mm and the bed level change to describe the available pores for emergence and the risk of displacements and physical damage. The simulated habitat suitability indices allow for a representation of physical habitats in the form of spatial distribution maps for different time-steps, time-series for different locations and an integrated habitat supply over the entire reproduction period. This provides highly valuable information about habitat dynamics as all spatially and temporally varying input variables are considered in the multi-step habitat modelling framework. Consequently a direct identification of occurring bottlenecks during the reproduction of brown trout is feasible and can be referred back to responsible habitat variables. In the case study it is found that the spawning and emergence stages are not limiting the reproduction success and the most restricting conditions occurred during hatching. These limitations are predominantly caused by critical temperatures during the winter season and critical permeability conditions due to sediment infiltration processes during the regulated flow period. The aggregated reproduction habitat suitability contains the summarized effects of all varying abiotic conditions during the reproduction period of gravel-spawning fish and allows for a quick identification of the availability and quality of reproductive habitats.

Although the obtained results provide valuable results it is worth noting that models in general are never able to fully reflect the dynamic behaviour of rivers and its ecological relations given their numerous and complex interactions. The simplification of the physical and ecological processes requires a well-founded verification of obtained simulation results against field observations and reference sites. The highest benefit of the proposed modelling framework comprises the spatial and temporal consideration of conventional and new habitat variables resulting in a detailed representation of habitat dynamic processes occurring in river reaches. Further, the presented work is the first attempt to simulate the quality of reproduction habitats for gravel-spawning fish using physical habitat modelling. Possible future applications predominantly include the support of ecological impact assessments but also the applicability as an instrument supporting the management and planning processes of restoration measures (e.g. for re-establishing reproducing fish population in rivers) as the simulation of reproduction habitats presents one fundamental process for the development of stable fish populations.

Zusammenfassung

Zielsetzung und Motivation

Die Komplexität und Dynamik fluvialer ökologischer Prozesse stellt äußerst hohe Anforderungen an die Entwicklung von Methoden und Modellen zur Unterstützung in ökologischen Bewertungen von Fließgewässern. Insbesondere die Interaktion zwischen abiotischen und biotischen Komponenten, die hohe räumliche und zeitliche Variabilität sowie die Interdisziplinarität der beteiligten Prozesse erschweren die Entwicklung geeigneter Modellierungs- und Prognosewerkzeuge. Die regelmäßige Erzeugung, Zerstörung und Erhaltung von charakteristischen Habitatmustern (Habitatdynamik) sind grundlegende Prozesse fluvialer Ökosysteme, die mit aktuell verfügbaren Habitatmodellen schwierig abzubilden sind und die Notwendigkeit der Weiterentwicklung von existierenden Ansätzen der Habitatmodellierung verdeutlichen.

Die vorliegende Arbeit befasst sich mit Prozessen aus der Hydromorphologie, der Fließgewässerökologie und des hyporheischen Interstitials, die interaktiv die Habitatqualität während der Reproduktion (Laich-, Inkubations-, Emergenzphase) von kieslaichenden Fischarten bestimmen. Die Motivation dieser Arbeit resultiert aus der wachsenden Anforderung dynamische Prozesse, wie die hydromorphologische und hyporheische Variabilität in die physikalische Habitatmodellierung von Fischen zu implementieren um somit die Simulation von dynamisch veränderlichen Habitateignungen zu ermöglichen. Der Fokus richtet sich hierbei auf morphodynamische Prozesse, wie Kornsortierungen (longitudinal, horizontal und vertikal), Infiltration von Feinsedimenten in das Korngerüst der Gewässersohle und Sohlumlagerungen, die einerseits notwendig sind um geeignete Habitate zu erzeugen aber andererseits auch limitierend wirken können. Um den Habitatansprüchen während der Reproduktion durch Modellierung gerecht zu werden besteht weiterhin der Bedarf an der Entwicklung eines geeigneten Indikators zur Beschreibung der hyporheischen Variabilität. Dieser soll dazu dienen den interstitialen Lebensraum während den Entwicklungsstadien des Inkubationszeitraums (Augenpunktstadium, Schlupfzeit und larvale Phase) entsprechend zu bewerten.

Das primäre Ziel ist daher die Entwicklung eines Modellsystems, basierend auf dem Prinzip der physikalischen Habitatbeschreibung um die räumlich und zeitlich variierenden Habitateignungen der einzelnen Entwicklungsstadien während der Reproduktionsphase von kieslaichenden Fischarten zu simulieren und zu einem aggregierenden Gesamtergebnis – der Reproduktionshabitateignung – zusammenzuführen. Diesbezüglich werden drei Hypothesen aufgestellt, die im Rahmen dieser Arbeit aufgenommen, diskutiert und beantwortet werden.

Hypothese 1: Ein 3-dimensionales Feststofftransportmodell ist in der Lage die maßgeblichen dynamischen fluvialen Prozesse, die einen Einfluss auf die Sedimentcharakteristik haben, ausreichend genau nachzubilden. Dies betrifft insbesondere Sohlhöhenänderungen, Kornsortierungen und Sedimentinfiltration.

Hypothese 2: Die räumliche und zeitliche Verknüpfung von Schlüsselfaktoren zur Beschreibung von interstitialen Lebensräumen über einen fuzzy-logischen Ansatz ist geeignet, die hyporheische Variabilität und ihren Einfluss auf das Interstitial hinsichtlich der Eignung als Reproduktionshabitats zu beschreiben.

Hypothese 3: Ein mehrstufiges fuzzy-logisches Modellsystem ermöglicht die Simulation dynamischer Habitateignungen für die Alters- und Entwicklungsstadien während der Reproduktion kieslaichender Fischarten, die zu einem aggregierten Gesamtergebnis – der Reproduktionshabitateignung – zusammengefasst werden können.

Reproduktion kieslaichender Fischarten und Habitatdynamik

Die einzelnen Entwicklungsstadien während der Reproduktion kieslaichender Fischarten stellen hohe Anforderungen an die abiotische Qualität des Lebensraums, die nicht mit statischen Faktoren beschreibbar sind. Die notwendige dynamische Berücksichtigung ergibt sich aus der mehrmonatigen Reproduktionsphase, die maßgeblich durch die hydromorphologische und hyporheische Variabilität geprägt ist und sowohl vielfältige als auch unterschiedliche Anforderungen an das Habitat stellt. Für die Laichphase sind regelmäßige Umlagerungen der Gewässersohle eine Grundvoraussetzung, um die Sohle aufzulockern und geeignete Korngrößenzusammensetzungen zur Verfügung zu stellen. Daher sind morphodynamische Auswirkungen von Hochwasserereignissen, insbesondere die Umlagerung von Sedimentschichten mit veränderter Kornsortierung, unverzichtbare Prozesse, die im Rahmen einer Habitatmodellierung zu erfassen sind. Für die Inkubationsphase dagegen ist eine stabile Gewässersohle erforderlich, um ein Ausspülen der Eier und Larven zu verhindern. Weiterhin ist das Inkubationshabitat maßgeblich durch die interstitialen Habitateigenschaften bestimmt, die sich maßgeblich über die Sedimentcharakteristik, sowie über die Temperatur- und Sauerstoffverhältnisse definieren. Morphodynamische Prozesse wie die Kolmation oder die Infiltration von Feinsedimenten führen zur einer Reduzierung des verfügbaren Porenraums und limitieren somit die Sauerstoffversorgung durch das Oberflächenwasser sowie den Abtransport von Stoffwechselprodukten. Der resultierende zur Verfügung stehende gelöste Sauerstoffgehalt wird weitergehend über hyporheische Austauschprozesse zwischen Grund- und Oberflächenwasser, sowie über die Respiration im Rahmen von biogeochemikalischen Prozessen definiert. Eine erfolgreiche Emergenz bedarf ähnlich stabiler Sohlverhältnisse wie in der Inkubationsphase, sowie ausreichend durchgängiger Porenräume, die den Aufstieg aus dem Kieslückensystem der Gewässersohle in die Freiwasserzone ermöglichen.

Um der Vielfalt der Habitatansprüche während der Reproduktion gerecht zu werden ist es daher nicht ausreichend die Sedimentcharakteristik über einzelne und statische Sedimentgrößen zu approximieren, wie es in vielen existierenden Habitatmodellen der Fall ist (z.B. mittlerer Korndurchmesser, dominierendes Substrat). Vielmehr gilt es die Dynamik der Sedimentcharakteristik sowie die Auswahl der Habitatvariablen entsprechend den Anforderungen an den Lebensraum anzupassen.

In diesem Hinblick ist speziell auch die Kolmation zu erwähnen, welche in einer Vielzahl von Publikationen als ein bedeutender Habitatparameter für Laich- und Reproduktionshabitate verwendet wird. Die Eignung als Habitatvariable wird allerdings durch zwei maßgebliche Faktoren eingeschränkt. Zum einen existiert keine einheitliche Definition der Kolmation und zum anderen ist die Kolmation nicht prognostizierbar. In der Literatur wird sowohl zwischen äußerer und innerer Kolmation als auch zwischen mechanischer, physikalischer oder chemischer Kolmation unterschieden. Häufig wird auch nur die sedimentologische Kolmation im Sinne einer „Verstopfung des Lückenraums mit Feinsedimenten“ als Definition verwendet. Weiterhin werden mikrobielle Prozesse (z.B. Biofilme), die zusätzlich den Porenraum im Kieslückensystem verschließen, unter dem Begriff der Kolmation aufgeführt. Zusammenführend kann die Kolmation als sedimentologischer und biogeochemikalischer Prozess verstanden werden, der sich durch eine Vielzahl von interaktiven dynamischen Teilprozessen kennzeichnet. Diese Komplexität erschwert die Erfassung der Kolmation als Habitatparameter, da sie messtechnisch schwierig zu erfassen ist und häufig nur durch visuelle Kartiermethoden annähernd abgeschätzt werden kann. Daraus resultiert allerdings nur eine Momentaufnahme und eine Prognose durch Modelle ist derzeit nicht möglich. Daher wird im Rahmen dieser Arbeit nicht die Kolmation als solche betrachtet, sondern ein Indikator für die hyporheische Variabilität entwickelt, der sich in Form einer räumlich und zeitlich variablen Interstitialhabitatqualität ausdrückt. Der Indikator orientiert sich dabei nicht am Prozess der

Kolmation, sondern stellt die hyporheische Variabilität den Ansprüchen kieslaichender Fischarten während der Inkubationsphase gegenüber.

Modellkonzept und Modellentwicklung

Um sowohl die vielfältigen Ansprüche der einzelnen Entwicklungsstadien während der Reproduktion, als auch die hydromorphologische und hyporheische Variabilität der abiotischen Habitatvariablen abzubilden, wird ein Modellsystem basierend auf dem Prinzip der physikalischen Habitatmodellierung entwickelt. Während für die räumliche und zeitliche Abbildung der Habitatvariablen das 3-dimensionale Feststofftransportmodell SSIIM2 verwendet wird, findet für die Verknüpfung von Abiotik und Biotik das multivariate fuzzy-logische Habitatsimulationsmodell CASiMiR Anwendung. Alle Habitatansprüche während den einzelnen Entwicklungsstadien der Reproduktion basieren auf einer im Rahmen dieser Arbeit durchgeführten Literaturstudie sowie der Expertise von Diplom-Biologe Johannes Ortlepp, der seit über zehn Jahren die Entwicklung der Bachforellenpopulation im Modellgebiet der Fallstudie untersucht und daher über die bestmöglichen Erfahrungen und Kenntnisse hinsichtlich der Habitatansprüche verfügt.

Insgesamt gliedert sich das Modellsystem in vier Hauptkomponenten. Die erste Komponente befasst sich mit der Erfassung der *hydromorphologischen Variabilität* des abiotischen Habitats. Der Fokus hierbei liegt in der numerischen Abbildung aller relevanten morpohodynamischen Prozesse, die die Reproduktionshabitateignung beeinträchtigen können. Insbesondere gilt es die Auswirkungen von Hochwasserereignissen auf die Sedimentcharakteristik im Sinne von Sohlhöhenänderungen und Kornsortierungen zu erfassen sowie während Niedrigwasserphasen die Infiltration von Feinsedimenten in das Korngerüst der Gewässersohle, die die Porosität und somit auch die Permeabilität der Gewässersohle beeinflussen. Besonders die Infiltration von Feinsedimenten ist bisher kein Standardergebnis numerischer Modellierung, da der Prozess eine Veränderung der Korngrößenzusammensetzung ohne Sohlhöhenänderung darstellt, der im Rahmen dieser Arbeit über eine geeignete Kalibrierungsstrategie approximiert wird.

Die zweite Modellkomponente befasst sich mit der *hyporheischen Variabilität*, die mittels multivariater Fuzzy-Modellierung die Schlüsselfaktoren Permeabilität, interstitiale Temperatur und hyporheische Respiration zu einer Interstitialhabitateignung verknüpft, und somit als Indikator für interstitiale Eigenschaften fungiert. Während die Permeabilität die Sedimentcharakteristik beschreibt und Informationen über die Transportkapazität von sauerstoffreichem Oberflächenwasser sowie den Abtransport von Stoffwechselprodukten zur Verfügung stellt, gibt die interstitiale Temperatur Hinweise bezüglich der Stoffwechselaktivität an, sowie obere und untere letale Temperaturgrenzen. Die hyporheische Respiration fasst den Sauerstoffbedarf von biogeochemikalischen Prozessen zusammen, welcher über Respirationsmessungen und über verfügbare Aufwuchsflächen von Mikroorganismen abgeschätzt wird. Aufgrund der unterschiedlichen Habitatanforderungen der Entwicklungsstadien während der Inkubationsphase (Augenpunktstadium, Schlupfzeit und larvale Phase) werden die Berechnungen zur Qualität des Interstitials für jedes Entwicklungsstadium separat durchgeführt. Des Weiteren wird das Fuzzy-Modell in jedem Element des Berechnungsgitters, sowie zu jedem Zeitschritt durchgeführt, um die räumliche und zeitliche Variabilität der Interstitialqualität adäquat abzubilden.

Die dritte Modellkomponente beinhaltet die *physikalische Habitatmodellierung* der einzelnen Entwicklungsstadien. Beginnend mit der Laichphase wird ein zweistufiges Fuzzy-Modell eingesetzt, das in einem ersten Fuzzy-Schritt die Korngrößenverteilung in die Sediment-Klassen Sand, Feinkies, Grobkies und Steine auswertet und in einer Laichsubstratqualität resultiert. Diese wird in einem zweiten Fuzzy-Schritt mit der hydrodynamischen Charakteristik in Form von Wassertiefen und Fließgeschwindigkeiten zu einer Laichhabitatqualität verknüpft. Insbesondere die Berücksichtigung von zeitlich variablen multifraktionalen Sedimentklassen stellt eine Erweiterung bisheriger Habitatmodellierungsansätze dar, da erstmals Ansprüche an die dynamische Entwicklung von Korngrößenzusammensetzungen in der Habitatmodellierung betrachtet werden, die es erlauben Ansprüche an den maximalen Feinsedimentanteil oder die maximal bewegbare Korngröße während des Schlagens von Laichgruben zu berücksichtigen. Die Habitatmodellierung für die Inkubationsphase wird ebenfalls über einen zweistufigen Fuzzy-Ansatz durchgeführt, wobei der erste Schritt die Simulation der Interstitialhabitatqualität beinhaltet, welche in einem zweiten Schritt mit den Variablen Sohlhöhenänderung und Richtung des vertikalen hydraulischen Gradienten kombiniert wird. Die Sohlhöhenänderungen erfassen hierbei die Gefährdung des Ausspülens von Eiern und Larven aufgrund von Erosionstiefen im Bereich typischer Eiablegetiefen, während die Richtung des vertikalen hydraulischen Gradienten Information über den Austausch zwischen Grundwasser und Oberflächenwasser gibt. Im Fall von infiltrierendem Grundwasser wird die Sauerstoffversorgung in den Entwicklungsstadien der Inkubationsphase limitiert, da Grundwasser generell über einen sehr geringen Sauerstoffgehalt verfügt. Die letzte Phase betrifft die Emergenz, welche über ein einstufiges Fuzzy-Modell abgebildet wird und die Habitatgrößen Sohlhöhenänderung, geometrischer Korndurchmesser und Fraktionsanteil < 8mm beinhaltet. Während der geometrische Korndurchmesser sowie der Fraktionsanteil < 8mm darauf abzielen die verfügbare Porengröße im Kieslückensystem der Gewässersohle anzunähern, berücksichtigt die Sohlhöhenänderung wiederum die Gefährdung des unbeabsichtigten Ausspülens.

Die letzte Modellkomponente beinhaltet die *Aggregation* der entwicklungsspezifisch simulierten Habitateignungen zu einer Reproduktionshabitateignung, welche über eine multiplikative Verknüpfung der minimalen Habitateignungen berechnet wird. Als Endergebnis repräsentiert die Reproduktionshabitateignung alle abiotischen Variablen während der Reproduktionsphase und ermöglicht eine übersichtliche Darstellung des verfügbaren Habitatangebots für die Reproduktion kieslaichender Fischarten.

Ergebnisse und Auswertungen

Die Untersuchungen zur Reproduktion von kieslaichenden Fischarten wurden am Beispiel der Bachforelle (*Salmo trutta*) im Fließgewässer Spöl, Schweiz durchgeführt. Die Untersuchungsstrecke im Spöl befindet sich unterhalb der Staumauer Punt dal Gall und ist durch eine, gegenüber dem ursprünglichen Mittelwasserabfluss, reduzierte Abflussregulierung charakterisiert. Die Besonderheit des Untersuchungsgebiets beinhaltet die Durchführung von jährlichen künstlichen Hochwasserereignissen mit dem Ziel den negativen Auswirkungen der Abflussregulierung (wie z.B. die Kolmation der Gewässersohle) entgegenzuwirken, um somit bestmögliche Reproduktionsbedingungen für die Bachforelle zu schaffen.

Für die Datenbasis und Verifizierung des entwickelten Modellsystems wurde von September 2009 bis Mai 2011 ein umfangreiches abiotisches und biotisches Monitoring durchgeführt, das insgesamt zwei Reproduktionsperioden (2009/2010, 2010/2011) mit je einem künstlichen Hochwasserereignis vor der Laichphase umfasst. Die Ergebnisse und Auswertungen sind im Folgenden hinsichtlich der Simulationen der hydromorphologischen Variabilität (Hypothese 1), der hyporheischen Variabilität (Hypothese 2) sowie hinsichtlich der physikalischen Habitatmodellierung inklusive der Aggregation zu einer Habitatqualität für die Reproduktion (Hypothese 3) zusammenfassend dargestellt und erläutert.

Hydromorphologische Variabilität (Hypothese 1)

Für die Abbildung der hydromorphologischen Prozesse wird das 3-dimensionale Feststofftransportmodell SSIIM2 sowohl auf die künstlichen Hochwasserereignisse als auch auf die regulierten Abflussverhältnisse während der Reproduktionsphasen im Fließgewässer Spöl angewendet. Die Kalibrierung des numerischen Modells wird anhand der Sedimentdaten in der ersten Reproduktionsphase (2009/2010) durchgeführt, während die Ergebnisse aus der zweiten Reproduktionsphase (2010/2011) zur Validierung verwendet werden.

Bezüglich der Simulation künstlicher Hochwasserereignisse ist SSIIM2 in der Lage die Höhen der Sohlumlagerungen sowie die Veränderung der Korngrößenzusammensetzungen ausreichend genau abzubilden. Jedoch existieren Diskrepanzen hinsichtlich der exakten räumlichen Darstellung von Sohlhöhenänderungen. Obwohl simulierte Anlandungs- und Erosionszonen den tatsächlich beobachteten Sohlhöhenänderungen ähnlich sind, zeigen die Modellergebnisse kleinräumige Abweichungen. Diese sind jedoch nicht zwingend auf die Modellqualität zurückzuführen, da die Anzahl der verfügbaren Sedimentproben zur flächigen Darstellung der extrem heterogenen Sedimentcharakteristik ebenfalls limitierend wirkt. Hinsichtlich der Reproduktion der Bachforelle, beziehungsweise der Nutzung als Laichhabitat, spielt die exakte räumliche Darstellung der Sohlumlagerungen eine weniger bedeutende Rolle, solange gewährleistet ist, dass eine Umlagerung mit entsprechender Kornsortierung in diesem Bereich stattgefunden hat. Die Umlagerungen und damit verbundenen Auflockerungen der Gewässersohle im Spöl bewegen sich vorwiegend im Rahmen von ±0.05 m, was hinsichtlich der typischen Tiefe von Laichgruben gerade als ausreichend bewertet wird.

Für die Simulation der Feinsedimentinfiltration in das Korngerüst von Gewässersohlen werden zunächst die physikalischen Rinnenversuche zur Sedimentinfiltration (Schälchli, 1993) im numerischen Modell reproduziert. Basierend auf diesen Voruntersuchungen sind einige Annahmen hinsichtlich der numerischen Abbildung von Infiltrationsprozessen zu treffen. Erstens wird die Annahme getroffen, dass das abgelagerte Feinmaterial in der obersten Sedimentschicht der Infiltrationsmenge in das Korngerüst entspricht. Dies widerspricht den Erkenntnissen aus den physikalischen Versuchen, da sich das Feinmaterial vorwiegend zwischen der oberen und der darunter liegenden Sedimentschicht ablagert und nahezu ungehindert durch die grobe oberste Sedimentschicht transportiert wird. Dieser ungehinderte Transport durch eine Sedimentschicht ist jedoch mit den derzeitig numerisch verwendeten Konzepten der vertikalen Kornsortierung nicht reproduzierbar. Eine weitere Annahme betrifft den Infiltrationswiderstand, welcher bei zunehmender Infiltration durch die Abnahme der verfügbaren Porengröße steigt. Dieser Widerstand wird über eine Anpassung der Hiding/Exposure-Funktionen in SSIIM2 approximiert, womit prinzipiell das Gleichgewicht zwischen Deposition und Resuspension gesteuert wird. Basierend auf diesen Annahmen und mit den Hiding/Exposure-Funktionen als Kalibrierungsfaktor können sowohl die Gesamtmenge als auch der zeitliche Verlauf des Infiltrationsprozesses numerisch nachgebildet werden. Die Übertragung der gewonnenen Erkenntnisse auf das Fließgewässer Spöl erfordert jedoch weitere Einschränkungen. Zum einen kann die Kalibrierung anhand von Hiding/Exposure-Funktionen nur konstant und statisch über das gesamte Modellgebiet und den kompletten Simulationszeitraum erfolgen und zum anderen ist eine Reduzierung der Sinkgeschwindigkeiten notwendig, um ein Gleichgewicht zwischen Deposition und Resuspension innerhalb der Reproduktionsphase zu vermeiden. Bezüglich der Verifizierung der Modellergebnisse stehen lediglich gemessene Infiltrationsmengen am Ende der Reproduktionsphase zur Verfügung, wodurch der zeitliche Verlauf der Infiltration nicht exakt verifiziert werden kann. Daher wird basierend auf der Annahme, dass der zeitliche Verlauf der Infiltration durch die semi-empirischen Gleichungen von Schälchli (1993) ausreichend genau approximiert wird, die Kalibrierung zusätzlich anhand der Ergebnisse des Ansatzes von Schälchli durchgeführt. Basierend auf dieser Modellierungsstrategie ist es möglich die dynamischen Infiltrationsprozesse am Spöl sowohl räumlich als auch zeitlich mit SSIIM2 abzubilden. Die Untersuchungsstrecke zeigt im Vergleich zu Literaturwerten relativ geringe Infiltrationsraten, was hauptsächlich auf die Lage unterhalb der Staumauer zurückzuführen ist, und Feinsedimente vorwiegend lateral über Niederschlagsereignisse und Schneeschmelze in das System eingetragen werden. Die mittleren Infiltrationsraten schwanken zwischen 0.03 kg/m²d und 0.07 kg/m²d, wobei höhere Infiltrationsraten vorwiegend in Bereichen mit sehr heterogenen Korngrößenverteilungen auftreten.

Die gewonnenen Erkenntnisse lassen hinsichtlich der Hypothese 1 folgende Schlussfolgerungen zu: Die hydromorphologische Variabilität hinsichtlich Sohlhöhenänderungen, Kornsortierungsprozessen und Sedimentinfiltration können mit SSIIM2 reproduziert werden, allerdings bedarf es hierfür tiefgreifender Annahmen und Vereinfachungen von physikalischen Prozessen. Des Weiteren sind die gewonnen Modellergebnisse stark von den umfangreichen Kalibrierungsmöglichkeiten numerischer Feststofftransportmodelle abhängig, mit denen eine große Bandbreite von Ergebnissen erzielt werden kann.

Hyporheische Variabilität (Hypothese 2)

Die simulierten Interstitialhabitateignungen - als Indikator für die hyporheische Variabilität - reflektieren die unterschiedlichen Ansprüche der Entwicklungsstadien während der Inkubationsphase. Die Modellergebnisse während des Augenpunktstadiums zeigen vorwiegend Eignungen in den Bereichen ‚sehr hoch‘ und ‚hoch‘, während die kritischsten Habitatbedingungen in der Schlupfzeit auftreten und Eignungen zwischen ‚hoch‘ und ‚gering‘ aufweisen. Die larvale Phase hingegen zeigt höhere Eignungen als die Schlupfzeit aber geringere Eignungen als das Augenpunktstadium. Diese Einteilung entspricht weitestgehend den Erkenntnissen aus Literaturstudien. Eine Analyse von Habitateignungsganglinien ermöglicht nun den Einfluss der einzelnen Schlüsselfaktoren zu ermitteln. Insbesondere während der Schlupfzeit treten Schwankungen der interstitialen Habitateignungen über eine oder mehrere Habitateignungsklassen auf. Diese sind vorwiegend auf den Einfluss der interstitialen Temperatur zurückzuführen, da diese räumlich betrachtet in allen Bereichen der Untersuchungsstrecke in gleichem Ausmaße auftritt und somit die vorgegebene konstante räumliche Verteilung der interstitialen Temperatur widerspiegelt. Bei Erreichen von Temperaturwerten (< 3°C) vermindert sich die Habitateignung, da diese hinsichtlich einer erfolgreichen Ei- und Schlupfentwicklung limitierend wirken. Der Einfluss der Permeabilität zeigt sich hauptsächlich durch unterschiedliche Eignungen bei gleichen Temperaturverhältnissen. Die kontinuierlich abnehmenden interstitialen Habitateignungen reflektieren die fortschreitende Infiltration von Feinsedimenten und den damit verbundenen Rückgang der Permeabilität. Der Einfluss der hyporheischen Respiration ist im Spöl eher als gering einzustufen, da nur in wenigen Bereichen in denen eine hohe Sedimentinfiltration und eine geringe Permeabilität vorhanden ist, kritische Werte erreicht werden.

Die Eignung des fuzzy-logischen Ansatzes zur Beschreibung des Interstitialhabitats als Indikator für die hyporheische Variabilität wurde anhand allgemeiner Indikator-Kriterien (Sensitivität, Interpretierbarkeit, Durchführbarkeit, Nachvollziehbarkeit) überprüft. Die Kriterien werden zusammenfassend als erfüllt bewertet, da insbesondere die Sensitivität hinsichtlich äußerer Einflussfaktoren, die Nachvollziehbarkeit des Lösungswegs und die Interpretierbarkeit der Ergebnisse durch das Fuzzy-Modell gegeben sind.

Basierend auf diesen Ergebnissen kann die Hypothese 2 zu weiten Teilen bestätigt werden, da die interstitialen Habitateignungen den Einfluss der Schlüsselfaktoren sowohl räumlich als auch zeitlich widerspiegeln und die Funktionalität als Indikator für die hyporheische Variabilität nachgewiesen wurde. Insbesondere die räumlich und zeitlich variierenden Habitateignungen erlauben eine exakte Identifizierung wann, wo und wodurch limitierende abiotische Habitatbedingungen im Interstitial auftreten. Einschränkungen sind hinsichtlich der unzulänglichen Betrachtung der hyporheischen Austauschprozesse zwischen Grund- und Oberflächenwasser zu machen, die einen wesentlichen Einfluss auf die abiotische Qualität von interstitialen Habitaten haben und in der vorgestellten Methode nur ansatzweise über die verwendeten Schlüsselfaktoren abgebildet werden. Zusätzlich sind weitere fundierte Verifizierungsmöglichkeiten zu empfehlen, die die Aussagekraft der Modellergebnisse erhöhen.

Physikalische Habitatmodellierung und Aggregation (Hypothese 3)

Die Habitatmodellierung für das Reproduktionshabitat der Bachforelle beinhaltet die Simulation von Laich-, Inkubations- und Emergenzhabitaten, wobei die Inkubationsphase weitergehend in Augenpunktstadium, Schlupfzeit und larvale Phase eingeteilt wird. Für jedes einzelne Entwicklungsstadium werden die räumlich und zeitlich variablen Habitatfaktoren über eine multivariate Fuzzy-Modellierung zu einer Habitateignung verknüpft.

Die Ergebnisse der Simulationen der Laichhabitatqualität in der Untersuchungsstrecke zeigen eine klare Dominanz der Laichsubstratqualität, während die hydraulischen Variablen hauptsächlich in den Uferbereichen limitierend wirken. Ein Vergleich mit tatsächlich geschlagenen Laichgruben liefert sehr gute Übereinstimmungen mit den simulierten Laichhabitateignungen die als ‚hoch' und ‚sehr hoch' eingestuft sind. Die hohe Qualität der Simulationsergebnisse wird insbesondere dadurch belegt, dass für zwei unterschiedliche abiotische Randbedingungen (2009, 2010) ähnlich gute Übereinstimmungen gefunden wurden. Während in der Laichphase 2009 insgesamt 19 % der Strecke mit 'hoch' und ‚sehr hoch' bewertet werden, ist für die Laichphase 2010 mit 23 % ein höheres Laichhabitatangebot verfügbar. Der relative geringe Unterschied wird durch die Gesamtanzahl an tatsächlichen Laichgruben (2009: 43 LP, 2010: 48 LP) belegt. Dies führt weiterhin zu der Schlussfolgerung, dass das in 2010 früher stattgefundene künstliche Hochwasser und die damit länger anhaltende Niedrigwasserperiode bis zur Laichzeit sich nicht negativ auf die Laichhabitatqualität auswirkt.

Die Simulation der Inkubationshabitate wird nur in Bereichen durchgeführt, in denen auch ein Ablaichen möglich ist, da nur dort ihre Qualität für die Reproduktion relevant ist. Eine wichtige Annahme wird hinsichtlich der zeitlichen Habitatdynamik getroffen. Treten limitierende Habitateignungen innerhalb eines Entwicklungsstadium ein, können diese nicht durch spätere höher geeignete Eignungen kompensiert werden. Dies trifft insbesondere auf die Inkubationsphase zu, da die Mortalitätsrate der Fischeier oder Larven nicht nachträglich kompensiert werden kann. Da allerdings kurzzeitig schlechte Bedingungen nicht zwingend zur Mortalität führen, wird dies im Fuzzy-Regelwerk durch eine Herabsetzung der Eignung um eine Eignungsklasse berücksichtigt. In der Untersuchungsstrecke am Spöl stellt sich heraus, dass aufgrund der reduzierten Abflussregelung keine Gefährdung durch Erosion während der Inkubationszeit besteht und Bereiche, in denen das Grundwasser in das Oberflächengewässer infiltriert, sich außerhalb der Laichareale befinden. Damit ist die Habitatqualität während der Inkubationsphase ausschließlich durch die Interstitialhabitatqualität definiert. Für alle Entwicklungsstadien wird ein zunehmender Rückgang der Eignungen simuliert, der die limitierenden Habitateignungen aufgrund kritischer Temperaturen und Permeabilitäten widerspiegelt. Ein Vergleich der Inkubationsphasen 2009/2010 und 2010/2011 zeigt, dass für 2010/2011 ein größerer Flächenanteil der Laichareale für die Inkubationsstadien als nicht geeignet simuliert wird, was vornehmlich auf die längere Niedrigwasserphase mit erhöhter Infiltration von Feinsedimenten und einem entsprechenden Rückgang der Permeabilität zurückzuführen ist. Um die Modellergebnisse zu verifizieren, werden die erhaltenen Habitateignungen mit den Überlebensraten der Schlupfzeit aus den künstlich erstellten Laichgruben verglichen. Der Vergleich zeigt lediglich eine sehr schwache Korrelation der ‚mittleren'

Habitateignung mit Überlebensraten zwischen 50 % und 70 %. Die ausgeprägte Variabilität der Überlebensraten innerhalb der Laichareale und auch innerhalb jeder Laichgrube deuten allerdings darauf hin, dass die beobachteten Überlebensraten nicht zwingend auf veränderte abiotische Eigenschaften zurückzuführen sind, sondern vielfältige weitere Ursachen haben können, wie z. B. Keim- oder Pilzinfektionenen oder Beeinträchtigungen während des Einbaus und Transport der Eier. Daher spiegelt der Vergleich zu den simulierten Habitateignungen nicht zwingend die Modellqualität wider.

Hinsichtlich des Emergenzstadiums wird für beide Reproduktionsphasen durchgehend eine ‚sehr hohe' Eignung erreicht. Dies legt nahe, dass die Emergenz hinsichtlich des Reproduktionserfolges von Bachforellen im Spöl nicht kritisch ist. In diesem Zusammenhang ist zu erwähnen, dass mit dem geometrischen Korndurchmesser und dem Fraktionsanteil von Korngrößen <8mm die Wahl der Habitatvariablen nicht optimal ist, da sich aus morphologischer Sicht weitaus besser geeignete Parameter, wie z.B. die Porosität anbieten. Für den Einfluss der Porosität stehen allerdings bislang keine biologischen Daten hinsichtlich des Habitatanspruchs vor, weshalb in dieser Arbeit die oben genannten Größen verwendet wurden. Zusammenfassend ist festzuhalten, dass sowohl die Laichphase als auch die Emergenzphase nicht limitierend für die Reproduktion sind und innerhalb der Inkubationsphase die maßgeblich kritischen Habitatbedingungen während der Schlupfzeit auftreten.

Der letzte Schritt des Modellsystems beinhaltet die Aggregation der einzelnen Habitateignungen zu einer Reproduktionshabitateignung mittels multiplikativer Verknüpfung der minimalen Eignungen in jedem Alters- und Entwicklungsstadium. Die multiplikative Verknüpfung berücksichtigt hierbei, dass ‚geringe' Habitateignungen in einem Reproduktionsstadium nicht durch eine ‚hohe' Eignung in einem anderen Stadium ausgeglichen werden können. Die Reproduktionshabitateignungen in der Untersuchungsstrecke weisen ein Spektrum von 0.00 - 0.25 auf, wobei zu berücksichtigen ist, dass eine Eignung von 0.25 ungefähr der Kombination von ‚hohen' Eignungen in jedem Reproduktionsstadium entspricht (0.75^5). Ein Vergleich der beiden Reproduktionsperioden anhand der WUA-Werte ergibt – normiert am Laichhabitatangebot – für beide Phasen einen ähnlichen Wert, woraus auf eine ähnliche Limitierung durch abiotische Randbedingungen während beider Reproduktionsphasen geschlossen werden kann. Allerdings verfügt die Reproduktionsperiode 2010/2011 über ein insgesamt höheres Laichhabitatangebot, wodurch, trotz längerer Niedrigwasserperiode, insgesamt 10 % mehr Fläche zur Reproduktion zur Verfügung stehen.

Prinzipiell kann Hypothese 3 durch die erfolgreiche Simulation der zeitlich variierenden Habitatqualitäten in den einzelnen Reproduktionsstadien und der anschließenden Aggregation zu einer Reproduktionshabitateignung bestätigt werden. Insbesondere die Berücksichtigung von räumlich und zeitlich variierenden Eingangsgrößen erlauben die Simulationsergebnisse in Form von Habitateignungskarten zu verschiedenen Zeitpunkten, Habitateignungsganglinien an verschiedenen Orten und als integrierendes Habitatangebot darzustellen und auszuwerten. Damit wird einerseits die Habitatdynamik beschrieben und andererseits bieten die Auswertungen die Möglichkeit limitierende abiotische Randbedingungen sowohl zeitlich als auch räumlich zuzuordnen. Einschränkend ist jedoch festzuhalten, dass insbesondere der hyporheische Austausch in Zukunft verstärkt in der abiotischen Beschreibung der Habitate zu berücksichtigen ist und eine fundierte Überprüfung anhand biologischer Untersuchungen notwendig ist, um die Belastbarkeit der Ergebnisse zu erhöhen. Wichtig ist zu erwähnen, dass die Resultate in Form von Habitateignungen keine Aussage hinsichtlich Überlebensraten liefern, da die Habitateignungen ausschließlich auf abiotischen Habitatfaktoren beruhen. Sie umfassen damit nicht die Gesamtheit der ökologischen Prozesse hinsichtlich der Reproduktion kieslaichender Fischarten liefern aber dennoch wichtige Informationen über die abiotischen Grundvoraussetzungen des Reproduktionserfolgs.

Da das hier vorgestellte Modellsystem nur an einem Fließgewässer und nur für die Reproduktion der Bachforelle angewendet wurde kann die generelle Funktionalität und Übertragbarkeit auf andere Fließgewässer oder andere kieslaichende Fischarten im Rahmen dieser Arbeit nicht gewährleistet werden. Insbesondere hinsichtlich der ökologischen Bewertung wird empfohlen, die Methode zunächst auf eine unbeeinträchtigte Referenzstrecke anzuwenden, um somit belastbare ökologische Aussagen und Bewertungen zu ermöglichen.

Fazit

Basierend auf dem vorgestellten Modellsystem, indem insgesamt 14 Habitatvariablen in ihrer räumlichen und zeitlichen Dynamik erfasst werden, kann die Eignung des Reproduktionshabitats für kieslaichende Fischarten über die Beschreibung abiotischer Variablen approximiert werden. Insbesondere die dynamische Betrachtung aller Habitatvariablen erlaubt die Identifizierung von limitierenden Habitatbedingungen, wie sie mit bisherigen Ansätzen der Habitatmodellierung nicht möglich ist. Obwohl die aufgestellten Hypothesen mit gewissen Einschränkungen im Rahmen dieser Arbeit bestätigt wurden, ist festzuhalten, dass Modelle nie die gesamte fluviale Dynamik und deren Interaktion mit ökologischen Prozessen abbilden können. Die Vereinfachung physikalischer und ökologischer erfordern eine ausführliche und wohlbedachte Verifizierung der erhaltenen Simulationsergebnisse anhand von Naturdaten und Referenzbedingungen. Die Weiterentwicklung der physikalischen Habitatmodellierung im Rahmen dieser Arbeit besteht maßgeblich aus der räumlich und zeitlich hochaufgelösten Verwendung von bestehenden und neuen Habitatvariablen. Diese erlauben eine detaillierte Abbildung der relevanten abiotischen Prozesse in Fließgewässern in ihrem zeitlichen Verlauf und somit Aussagen über die Habitatdynamik. Des Weiteren stellt das Modellsystem erstmals den Versuch dar, die Reproduktionshabitate von kieslaichenden Fischarten im Rahmen einer physikalischen Habitatmodellierung abzubilden. Aufgrund der beinhalteten Dynamik und der Prognosefähigkeit des Modellsystems bestehen Anwendungsmöglichkeiten vorwiegend im Rahmen von ökologischen Untersuchungen und Bewertungen, aber auch in der Planung und dem Management wasserwirtschaftlicher und wasserbaulicher Maßnahmen, die zum Beispiel auf eine Wiedereinführung von reproduzierenden Fischpopulationen abzielen, da die Simulation von verfügbaren Reproduktionshabitaten eine fundamentale Grundlage für die nachhaltige Entwicklung von stabilen gewässertypischen Fischpopulationen ist.

PART A: Background & Basics

A.1 Introduction

A.1.1 Background

Fluvial ecosystems are characterized by a tremendous variability of biological, physical and chemical processes operating at multiple spatial and temporal scales (Wohl et al., 2007). The inherent complexity in the relationship between abiotic and biotic ecosystem functions constitutes a challenge in understanding the functionality of fluvial ecosystems. Ecosystems are naturally governed by hierarchical regional, watershed and reach scale processes controlling flow and sediment regimes as well as riparian and aquatic habitat dynamics and biota (Nilsson et al., 2005; Egger et al., 2007). Rivers have always been magnets for human settlements as they provide a variety of fluvial ecosystem services in terms of drinking water, irrigation, hydropower generation, recreational opportunities and habitat for economically important fisheries (Poff et al., 2003). Through these direct and indirect human influences fluvial ecosystems have suffered a long history of degradation (Maddock, 1999). Channel modifications, water diversion, aligning of riverbeds, navigation, agricultural drainage and flood protection are river engineering measures to improve the living standard of human beings but often at the expense of these fluvial ecosystems (Revenga et al., 2000). Moreover, both the rapid growing human population and the uncertainty about future water resource availability emphasize the importance of expanded water resources planning and development. The benefits to human society by maintaining ecosystem services, together with the enormous costs and difficulties of restoring degraded ecosystems have led to an increasing ecological awareness to integrate the principles of fluvial ecological functions in sustainable water policy, resources planning and management (Poff, 2009). This paradigm also elucidates the need for interdisciplinary collaboration between river engineers, scientists and stakeholders to advance the understanding of fluvial ecosystems and to develop innovative methods, models and tools to face the competing objectives between river utilization and river ecology.

The EU Water Framework Directive (WFD) provides an integrated approach to manage the three key components of fluvial ecosystems: water quantity, water quality and physical habitat (Commission, 2000). Thus the WFD assumes links between aquatic biota and the abiotic environment (Conallin et al., 2010; Sullivan et al., 2006). This assumption also provides the basis for aquatic habitat simulation tools in modelling the biotic response of indicator species to changing environmental factors using biota-physical relationships. Although these habitat models are able to detect ecological bottlenecks in river systems and are a valuable tool for integrated river management (Poff et al., 2003), they are criticized for neglecting relevant processes to derive assessments about the status of river ecology (Bain, 1995; Wheaton et al., 2010). Natural river dynamics like flow variability, sediment dynamics or biological interactions are components that are not yet fully considered in habitat modelling. Moreover the quality and usefulness of habitat models depends strongly on the quality of the input data. The state-of-the-art habitat modelling techniques mainly considers the standard habitat parameters water depth, flow velocity and dominant particle size (e.g. Harby et al., 2004). So far, the hydraulic conditions for a certain flow range or a single event are simulated using 1D-, or 2D-hydrodynamic-numerical modelling tools that are able to predict water depth and flow velocity for steady and unsteady flow. But the sediment characteristic is generally mapped by visual observation for only one specific situation and the distribution of sediments remains constant for different flow rates lacking the consideration of morphodynamic processes and temporal varying sediment characteristics (Wieprecht et al., 2007). However, morphodynamic processes play a key role for the ecological integrity of river habitats (Brodeur et al., 2004; Pasternack et al., 2004; Wheaton et al., 2010).

A.1.2 Motivation and objectives

According to Poff et al. (2010) flow and sediment regimes are the master variables in shaping fundamental ecological characteristics. Especially the dynamic interactions between hydrodynamics, morphodynamics and the aquatic environment are the foundations of fluvial ecosystems. In natural alluvial streams the biotic and abiotic processes adapt with each other forming an ecological state of dynamic equilibrium. Given to the anthropogenic development and utilization of rivers and the consequently altered flow and sediment regimes this dynamic equilibrium is thrown out of balance leading to depleted biodiversity and degraded ecosystems (Hupp et al., 2010). Many authors have reviewed the impacts of flow regulation on riverine ecosystems (e.g. Richter et al., 1997; Murchie et al., 2008) and one of the most common abiotic consequence is the decreasing frequency and magnitude of floods and sediment-transport events and the lacking regular disturbances of the sediment characteristics of riverbeds (Downes et al., 2003). Another significant abiotic impact are the long low flow periods with a constant discharge limiting fine sediment transport and contributing to instream fine sediment accumulation (Baker et al., 2010). Both morphological processes are characterized by a highly dynamic behaviour affecting directly the sediment conditions of riverbeds and subsequently the habitats of aquatic species that have life-cycle stages associated with sediment characteristics. Especially the development of fish embryos in the hyporheic interstitial zone is detrimentally affected by the infiltration and accumulation of fine sediments. The infiltrating fine particles reduce the pore space, substrate permeability and intragravel velocities leading to a restricting supply of well-oxygenated surface water to the developing embryos and larvae (Wu, 2000; Heywood & Walling, 2007). Thus, the intrusion of fine particles into the hyporheic interstitial represents a major limiting factor for reproduction of gravel-spawning fish (Chapman, 1988; Ingendahl, 2001; Malcolm et al., 2003; Greig et al., 2005; Sear et al., 2008). Current physical habitat simulation tools are not able to address the fluvial dynamic processes such as the redistribution, sorting, infiltration and mobilization of particles, although these processes on the one hand are often are a prerequisite for the creation of suitable spawning habitats and on the other hand are the major drivers for limiting distribution and abundance of riverine species (Yitian et al., 2007). The motivation of the present study is based on the growing need for predicting and quantifying these morphodynamic processes and linking them to a biological response using adequate simulation tools to make habitat predictions more reliable in considering habitat dynamics which is fundamental for managing flow and sediment regimes as well as for any habitat restoration measure.

Following this motivation this thesis intends to advance the habitat simulation tool CASiMiR (Computer Aided Simulation Model for Instream Flow Riparia) developed at the Institute of Hydraulic Engineering of Universitaet Stuttgart (Jorde, 1996; Schneider, 2001). CASiMiR is improved by implementing morphodynamic processes in physical habitat modelling using results of the 3D-sediment-transport model SSIIM (Sediment Simulation in Intakes with Multiblock option) developed by Olsen (2010) at the Norwegian University of Science and Technology (NTNU). The overall goal is to simulate the suitability for reproduction purposes of gravel-spawning fish considering additionally an indicator for the variable processes in the hyporheic interstitial as the early life-stages during the incubation period are highly vulnerable to any morphodynamic changes (Schiemer et al., 2003). Thus, the proposed habitat modelling framework aims to dynamically assess habitat quality from spawning to emergence and integrate the intermediate results of each life-stage to an aggregated parameter, the reproduction habitat suitability. In the future, this modelling concept might be helpful in reintroducing gravel-spawning fish species and to establish reproducing fish populations. Furthermore, it should be able to predict the impacts of morphodynamic changes on fish habitats supporting planning and management strategies in water resources management.

To address this challenging goal severe requirements on the modelling framework are demanded. Firstly, all relevant morphological processes including interstitial sediment dynamics have to be considered and quantified. Secondly, the impacts of these dynamic changes on the interstitial habitat quality for reproductive purposes of gravel-spawning fish have to be included in a quantitative and predictable manner, and thirdly, the habitat quality for each life-stage during the reproduction period has to be determined and aggregated to an indicator called reproduction habitat suitability. Accordingly, this thesis focuses three hypotheses:

Hypothesis 1: *A highly sophisticated numerical 3D-Sediment-Transport-Model is able to simulate all fluvial dynamic processes influencing sediment characteristics. This includes bed level changes, bed/suspended load and sorting of grain sizes but also the accumulation of fine sediments in the interstices of a gravel river bed leading to a reduction of substrate permeability.*

Hypothesis 2: *Linking the temporally and spatially variation of key factors describing the interstitial habitat via a multivariate fuzzy-logical approach is an appropriate method to describe the hyporheic variability and its impact on the suitability of reproductive habitats for gravel-spawning fish.*

Hypothesis 3: *A multi-step fuzzy-logic habitat modelling framework simulating the time-dependent habitat suitability for the whole reproduction period, considering the spawning, the incubation and the emergence stage, allows an assessment of the reproduction habitat suitability of river reaches by aggregating the single habitat indices.*

As fuzzy modelling allows dealing with the inherent uncertainty of ecological variables, and the ability to work with non-linear relationships between them, this technique has gained rising popularity in the modelling of ecosystem processes and in ecological assessments (Adriaenssens et al., 2006). The proposed modelling concept also bears a large uncertainty given to numerical computations of morphodynamic processes, measuring ecological and physical variables in the river and the hyporheic zone and in defining habitat requirements for the life-stages during reproduction. Given the complex nature of sediment-transport processes, the quality of results of numerical modelling depends on how well the physical processes are mathematically described through governing equations, boundary conditions, empirical formulas and how accurately the differential governing equations are discretized using numerical schemes (Wu, 2007). Moreover the accuracy of the proposed modelling framework depends on the quality of input data. Measuring ecological variables and physical parameters in the river and especially in the hyporheic zone to obtain information about the ongoing processes are characterized by a high spatial and temporal variability (Malcolm et al., 2003; Borchardt & Pusch, 2009) that currently cannot be measured representatively. To save time and avoid labour-intensive measurements, input data are commonly interpolated temporally and spatially including an uncertainty regarding the interpolation method and measurement resolutions. Further, the relations between physical and ecological components regarding the reproduction of gravel-spawning fishes are not exactly known nor can be described analytically using exact functions or equations (Schneider, 2001). Nevertheless, given the experience of decades of fisheries research dealing with the reproduction of gravel-spawning fish (especially salmonids (e.g. Saltveit, 2006; Cocan et al., 2010)) these relations might be estimated including a kind of cognitive uncertainty. To meet all these kinds of uncertainties in modelling, measurement techniques and physical-biota relations makes the fuzzy-approach to the ideal method for simulating the reproduction period of gravel-spawning fish considering hydromorpohological and hyporheic variability as it is dealing with both kinds of uncertainty: data uncertainty and cognitive uncertainty.

Therefore, the goal of the modelling concept is not to simulate the reproduction success in the form of survival rates of single redds but to address the suitability of typical reproductive areas such as the transition zones between pools and riffles (Tonina, 2005) comprising several redds and to investigate how these areas react on changing morphodynamic processes induced by floods or low flow periods.

A.1.3 Outline of the work

This section briefly outlines the organisation of this thesis to provide a quick understanding of the workflow and the various topics that are discussed within this thesis. This dissertation consist of five main parts, A, B, C, D and E. Firstly, the background and basic information are given in part A. Part B contains information about the necessity of simulating habitat dynamics and emphasizes the formulated hypotheses in this thesis, and part C includes the development of the multivariate habitat modelling framework to simulate the reproduction of gravel-spawning fish species. The application and results of the modelling framework are presented in a case study in part D. The thesis is concluded with part E, summarizing the obtained results and giving an outlook into future research needs.

Following the introduction, part A consists of two major blocks. The first one includes information about fluvial dynamic processes in rivers including morphological and ecological processes and their influence on the hyporheic interstitial. Firstly, the wide area of river morphology is described by hydrogeomorphological aspects and their occurring scales. Secondly, information regarding the fundamentals in sediment-transport processes is presented. Special consideration is taken with regards to the colmation process, providing information about available definitions and descriptions and the involved processes and parameters. Further background information is given about ecological processes including the role of habitats, scales, ecosystem functions and services and ecological indicators. Moreover, a detailed literature review about the requirements of gravel-spawning fish during reproduction is presented. Lastly, a definition of the hyporheic interstitial is given, including both morphological and ecological aspects in relation to the reproduction of gravel-spawning fish. The second block contains information about the numerical modelling of morphodynamic processes and habitat modelling. Following the mathematical description of morphodynamic processes, the limitations of state-of-the-art models are elucidated, and a brief introduction into the applied sediment-transport model SSIIM2 is given. In terms of habitat modelling, a review of different model types in linking abiotic habitat variables to biological responses is presented with information about general limitations in applying habitat simulation tools. Finally, the functionality of the applied habitat model CASiMiR with is multivariate fuzzy-logical approach is described at the end of part A.

Part B consists of three parts according to the formulated hypothesis in this introduction and begins with the bottleneck of missing morphodynamic processes in current habitat models. This section continues by providing an overview of available methods to include those processes in habitat modelling, leading to hypothesis 1 that describes the requirements on numerical sediment-transport models for dynamic habitat modelling. Secondly, the indication values of different indicators describing the interstitials of river beds are compared and evaluated in terms of the reproduction of gravel-spawning fish. Typical particle size analyses are contrasted to sediment infiltration and colmation processes, what leads to hypothesis 2 that includes a fuzzy-approach to calculate an interstitial habitat suitability comprising parameters to describe the hyporheic variability. Lastly, currently available approaches to simulate the reproduction of gravel-spawning fish are presented, ranging from empirical functions to combined habitat-population models resulting in hypothesis 3, which includes a combination of separately simulated habitat suitability indices for the different life-stages during reproduction.

The modelling concept and framework used to simulate the reproduction of gravel-spawning fish is presented in part C. It contains detailed information about the different modelling steps specifying the required input parameter, the data requirements and the expected model outputs for each step accordingly. The modelling steps are subdivided into numerical modelling of hydromorphological variability, the simulation of hyporheic variability in terms of interstitial habitat suitability (IHS), the simulation of habitat suitability indices (HSI) for spawning, incubation and emergence period and the aggregation of the single habitat suitability indices to a reproduction habitat suitability (RHS). Part C is concluded with a brief overview of model applicability and limitations.

The application of the developed modelling framework is the primary focus of part D. Previously the numerical model SSIIM2 is tested to simulate sediment infiltration processes in a rectangular flume where experimental data of sediment infiltration processes were available. The entire modelling framework was applied in a case study in the Swiss National Park at the River Spoel. Part D includes detailed information about the study site and the conducted abiotic/biotic monitoring including two reproduction periods (2009/2010, 2010/2011). The simulation results are illustrated for hydromorphological variability including the numerical simulation of artificial flooding and sediment infiltration using the numerical model SSIIM2. Additionally, the interstitial habitat suitability and the habitat suitability indices for the different life-stages during reproduction using the fuzzy-approach of CASiMiR with the subsequent aggregation to a reproduction habitat suitability (RHS) are presented. The results obtained are calibrated based on the reproduction period of 2009/2010 while the same parameter configurations and model setups are used for validation purposes for the reproduction period of 2010/2011. The results of each modelling step are then discussed in terms of uncertainties and reliability and compared to the formulated hypotheses in this thesis.

Part E concludes this thesis with a summary including a verification of the formulated hypothesis and related future research needs.

A.2 Fluvial dynamic processes

This chapter focuses on the dynamic behaviour of fluvial ecosystems as they play a central role in this thesis. From a physical process understanding, fluvial ecosystems may best be described as an open dissipative process-response system which self-organizes in response to external forcing (Molnar, 2010). The major external forces are hydrological variations with changing sediment loads influencing structure and function of aquatic communities within the river channel, on the floodplains and the hyporheic zone (Maddock et al., 2008; Richter et al., 1997). This chapter provides information about the major morphodynamic processes, followed by a section comprising ecological processes and lastly provide insights in interstitial processes in the hyporheic zone.

A.2.1 Morphodynamic processes

A.2.1.1 Hydrogeomorphological aspects

As a part of the hydrological cycle, all rivers transport water, sediments and debris from areas of high to low elevation. With precipitation-runoff events comes the movement and shaping of inorganic material from terrestrial environments to rivers (Schiff et al., 2006). This leads to the central theme in fluvial geomorphology that alluvial rivers determine the location and shape of their channels trough complex interactions among hydrology, geology, and morphology (Richards, 1982; Yitian et al., 2007), or simply hydrogeomorphology (Sidle & Onda, 2004). Over time fluvial systems are affected by extrinsic and intrinsic factors inducing river responses to achieve a balance between transport capacity and available sediment load. Extrinsic variables are parameters a river cannot control, for instance climate, sea level, tectonics and inherent geologic frameworks (Phillips, 2010). Therefore the fluvial system must adjust by changing slope, width, grain sizes, roughness and the degree of braiding or sinuosity, the so-called intrinsic controls (Allen & Castillo, 2007). According to these river responses it can be stated that fluvial systems tend to respond to disturbances by moving to an equilibrium state using morphodynamic processes.

Given these geomorphic processes, certain river types can be derived according to different control criteria as it is presented in Fig.A.2.1.

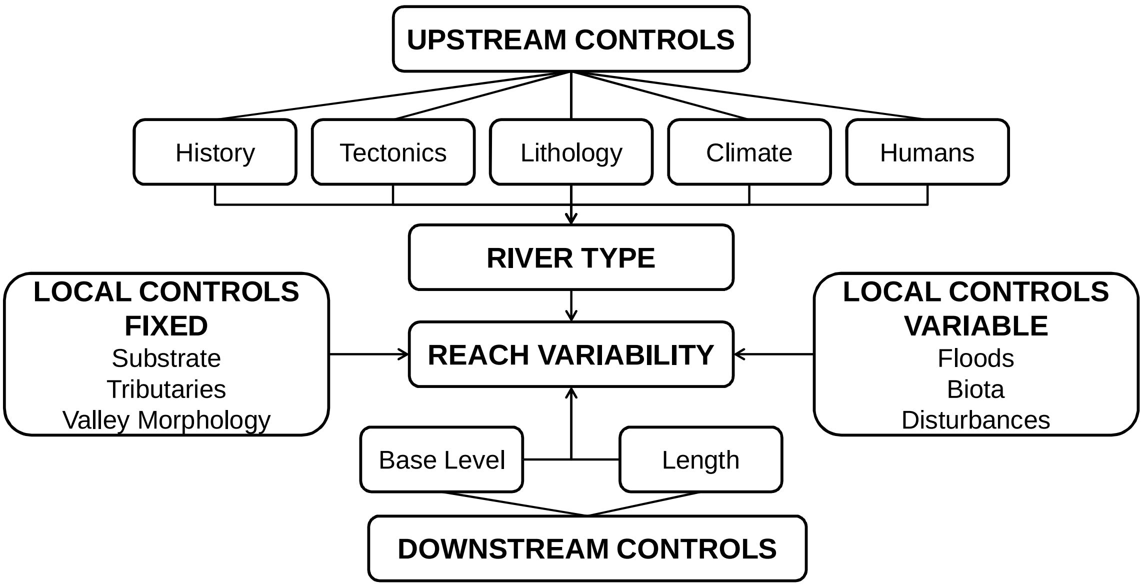


Figure A.2.1: Controls on geomorphic variability (modified after Schumm, 2005; Phillip, 2010)

Schumm (2005) distinguishes between upstream, downstream, and local controls. The upstream criteria comprise extrinsic variables that interact with each other, defining the quantity and quality of discharge and sediments, while the downstream controls may influence mainly the longitudinal gradient of the river (Phillips, 2010). Local variables are further subdivided into fixed parameters that only vary over long time scales (years/decades), such as temperature, substrate delivery or valley morphology and variable controls that vary on a shorter time-scale such as floods, disturbances or biota (days/weeks).

However, although the geomorphic processes defining and creating characteristic bed features on different spatial scales is still a challenge in geomorphic science (Bettes, 2008), it is well known that they are formed by the erosion and deposition of the channel according to channel evolutionary adjustment processes to achieve a dynamic equilibrium. Typical geomorphic features describe the horizontal river shape as straight, braided or meandering as well as the vertical river shapes as riffles, runs, pools and glides that occur in typical sequences depending mainly on the river width and gradient (Bettes, 2008).

The importance of natural hydrological variability and sediment conditions is also reflected in the permanent interactions between flowing water and sediments. An increase of flow by a factor of 15 can increase sediment-transport by almost a thousand fold (Bettes, 2008) resulting in continuous changes in the sediment compositions that are in motion, and on the riverbed. Significant quantities of sediments are moved during a few flood events per year, while the transport rates of sediments during low flow periods are small in comparison. This underlines the high sensitivity of sediment characteristics to variable flow conditions, especially to the magnitude, duration and frequency of peak flows.

The extensive alteration of fluvial systems by humans can be both extrinsic and intrinsic stressors for river morphology. In terms of economic, social, technological and cultural issues, anthropogenic influence is certainly an extrinsic factor but in terms of the interrelationships between hydrological processes and sediment loads human impacts are direct and intrinsic. Humans have influenced erosion and sediment production and sediment transport much more than any natural driving force. Syvitski et al. (2005) found that humans have increased sediment production by engineering measures leading to soil erosion and at the same time decreased it by construction of dams leading to a final consequence of an overall loss of sediment delivery to the ocean. The modification of flow and sediment regimes through dams or diversions is probably the most common human impact on fluvial systems. Today there are more than 45.000 dams above 15 m high capable of storing 15 % of the total annual river runoff globally. Today more than 60 % of the large river systems are fragmented by dams (Nilsson et al., 2005).

Consequently, humans have transformed these rivers from dynamically active and spatially complex systems to more static and homogenous ones, disturbing the natural flow paradigm (Richter et al., 1997). Moreover, dams interrupt the longitudinal connectivity of fluvial systems, which affects sediment-dynamics (Kondolf, 1997). Upstream of the dam the sediments are trapped in the reservoir, a severe sediment deficit is created downstream of the dam. As fluvial systems tend to a dynamic equilibrium, they directly adjust their channel morphology by disturbing natural geomorphic and ecological processes. If no or less sediment supply is provided by tributaries the downstream river has to erode from banks and from the riverbed to compensate for the limited supply leading to river incision. (Brandt, 2000). Simultaneously, the overall reduction and regulation of flow decreases the transport capacity resulting in a decreasing potential for erosion and aggradations (Petts & Gurnell, 2005). One consequence of the decreased transport capacity is selective erosion below dams as the sediment-transport capacity is not sufficient to move all available particle sizes resulting in a progressive coarsening of the surface bed material, forming an armoured layer consisting of large gravels, cobbles and boulders that can limit the ultimate depth of incisions (Kondolf, 1997). An additional impact is the change in instream sedimentation processes. Given the reduced transport capacity depositing fine sediment can accumulate on and in the river bed homogenizing the gravel river bed, decreasing the mean particle size and permeability and diminish the geomorphic heterogeneity (Baker et al., 2010). Both of these vertical sorting processes - armouring and embeddedness - are natural morphodynamic processes and the degree of severity varies with channel characteristics, sediment loads and available particle size distributions. Armouring coarsens the most upper sediment layer allowing fine sediments to intrude in deeper sediment layers where they are flow-protected and can accumulate forming a nearly impermeable layer. In dynamically active fluvial systems with periodically occurring bed alteration the armoured layers are regularly entrained and the fine materials are washed out of the interstitials leading to regular renewals and mixing processes of sediment characteristics. Due to flow regulation these flow peaks are suppressed resulting in static riverbed conditions supporting the severity of armouring and embeddedness.

A.2.1.2 Morphological scales

The enormous range of geomorphic and morphodynamic controls cover a spectrum of spatial and temporal scales ranging from > 10^8 m² in the form of eco regions, to < 10^{-4} m² in particle size compositions, and from > 10^6 years considering tectonics to < 10^{-7} years in local sediment dynamics (Minshall, 1988). This has led to the development of hierarchical nested models (e.g. Frisell et al., 1986; Poole, 2002). Tab.A.2.1 provides the hierarchical concept of geomorphic processes in rivers (modified after Brierley & Fryirs, 2005).

Table A.2.1: Hierarchy of temporal and spatial scales of morphodynamic processes (modified from Brierley & Fryirs, 2005)

spatial scale	time scale (persistence)	processes/parameters
eco-region	10^5-10^6 a	tectonics, geology, valley shape, holocene alluvium, lithologic and climate controls
catchment	10^5-10^6 a	shape, drainage density, geological features, hill slopes, tributary-trunk interactions, sediment delivery
segment	10^1-10^4 a	characteristic fluvial corridors of interactions between channel, riparian zone, floodplain and alluvial aquifer
river	10^0-10^2 a	aggradation/degradation, channel and bank stability, meandering, braiding, sinuosity, riffle-pool-sequences
meso-scaled bed forms	10^{-1}-10^1 a	morphological features like pools, riffles, cascades, runs, point bars, sediment distribution, sediment diversity
micro-scaled bed forms	10^{-2}-10^{-4} a	grain size composition, sorting processes, shape of grains, sediment infiltration, armouring, porosity, permeability

In hierarchically nested classifications, lower-level components are completely encompassed by the next higher level, whereby levels are separated by different characteristic rates of processes such as behavioural frequencies, response time, persistence time etc (Wu & David, 2002). Higher levels in hierarchical morphological systems are characterized by a slow recovery time and a low sensitivity to disturbances, while lower levels show shorter recovery times and a high sensitivity to disturbances. Further, there are trans-scale linkages between adjacent levels. While the upper level exerts constraints to the lower level (e.g. as boundary conditions) the lower level provides initial conditions to the upper level. Today these trans-scale processes (top-down/bottom-up) provide a foundation for understanding the geomorphologic dynamics of fluvial systems. Many geomorphic studies have addressed the structure and dynamics at multiple spatial-temporal scales (Poole, 2002). In geomorphic classifications the top-down approach dominates as, for instance a given geology and climate would tend to similar river characteristics. This asymmetric control of small-scaled features by larger-scaled characteristics implies to look beyond local site aspects when deriving catchment controls (Piégay & Schumm, 2003) and that care must be taken when smaller phenomena are used to explain larger ones (Wolfert, 2001).

For developing methods, models or other tools, the scale question is of major importance as relationships between scales and their significance in determining system functionality defines processes and model parameters. To gain information on larger scales (eco-region, catchment, segments) several geomorphic classification schemes have been developed. For instance, Rosgen (1996) used variables such as the number of tributaries, entrenchment ratio, depth/width ratio, sinuosity, slope, and bed material to characterize rivers in a geomorphic and morphologic way. On the segment and river scale the widely used diagram of da Silva (1991) can be applied to characterise river shape and bed morphological characteristics. She uses four parameters: river width, water depth, slope and characteristic particle size. Depending on the different ratios of these delineation criteria, the bed morphology can be characterized as straight, braided, meandering or having alternate bars. For meso-scaled bed forms Montgomery and Buffington (1998) used distinct river reach types as a function of sediment source, transport and river response. They divide bed forms along a longitudinal gradient including cascades, step-pool-sequences, pool-riffles sequences and plane beds.

In addition to these classification methods, various conceptual, empirical, and analytical modelling types are available for geomorphic assessments but most of them are not able to deal with spatial and temporal dimensions (Darby & van de Wiel, 2003). This is the advantage of numerical simulation tools, which are rapidly increasing in fluvial geomorphologic studies. According to Darby & van de Wiel (2003) the development of numerical morphological tools can be categorized into four groups dealing with solute transport, total transport, bed level change, and planform change. Numerical models cover a wide range of spatial and temporal scales varying from detailed predictions of morphodynamic process in a few meters of a river reach, to the evolution of several kilometres over tens and hundreds of years. However the feasibility of numerical models is strongly related to the modelling purpose and the required accuracy. For instance, simulating the sediment balance of the whole River Rhine or the vertical sorting processes in a short river reach, means to use completely different modelling techniques in terms of dimensionality and temporal and spatial discretizations.

The focus of the proposed modelling framework in this work is dealing mainly with micro-scaled bed forms and to a lesser extent with meso-scaled bed forms as typical reproduction areas of gravel-spawning fish can be found in pool-riffle-systems and depend strongly on local sediment characteristics. The temporal scale encompasses several months up to a year according to the incubation period of eggs and larvae in the hyporheic interstitial and the consideration of hydrological events before the spawning season. To do reliable morphodynamic modelling on the micro-scale the fundamental processes of sediment transport have to be considered as they are described in the next section.

A.2.1.3 Fundamentals of sediment transport

According to Wu (2007) sediment transport processes are among the most complex and least understood phenomena in nature and researchers worldwide are trying to address present problems in river engineering by deriving methods, approaches and models to understand these complex processes. This section does not claim to encompass the total range of sediment-transport phenomena but focuses on fundamental processes and parameters that are relevant for this thesis concerning typical gravel bed rivers. Therefore, aspects that might be important in other contexts are neglected here, including cohesive materials, bed forms like dunes/anti-dunes and downstream fining.

Sediment sources and transport types

The ultimate source of sediments originates from complex systems involving mainly tectonic, weathering and gravity-driven processes of the underlying rock in drainage basins (Nicols, 2009). Depending on the type of rock, denudation process, climate and vegetation cover, the broken solid particles are transported from their respective sources to river systems, by fluvial, aeolin or glacial processes in form of silt, clay, sand or less easily as cobbles and boulders. The total sediment outflow of catchments is called sediment yield, yet represents only a part of the total sediment production in catchments, as sediment masses may deposit before they reach river systems. Therefore, the sediment yield ratio, defining the reduction in sediment mass from the source to a measuring station in relation to the catchment area is commonly used to estimate the amount of sediments entering a river (Graf et al., 2010).

According to Mikos (2005) an important source of sediment in rivers is geological soil erosion which occurs as surface removal in the form of sheet erosion, rill erosion or deflation induced by precipitation and its runoff. Another important sediment source in rivers originates from gravity driven phenomena like rockslides, debris flows or mudflows. Once sediments enter a river, they may remain in place or be transported downstream. Typically the size of bed material is characterized by strong longitudinal variations that are divided into zones of sediment production, transport zones and deposition zones. One significant process is the reduction of particle size along a river, referred to as downstream fining, induced by abrasion and selective transport resulting in particle sorting processes according to transport capacity (e.g. Frings, 2008).

Traditionally, sediment load has been subdivided by source or type of transport (Einstein et al., 1940). In terms of sediment source, the total sediment load is split into bed material load and wash load (Wu, 2007). The bed material load is made of sediments from the river bed that continuously exchanges with the bed material and thus contributes to bed morphology. The wash load consists of sediments that have been flushed into the river from upstream sources (denudation processes) and are generally fine-grained and rarely exchanges with bed material. Subdividing by transport type, the sediment load is split into bed load and suspended load. The most important feature of bed load is the intermediate interaction with the river bed as bed load transport is usually described as rolling, sliding, hopping, or bouncing. Given these interactions bed load transport can be considered as a geomorphic agent exerting a fundamental control on the form and pattern of rivers (Hicks & Gomez, 2003). The distinction between bed and suspended load is required, as for example bed material load in upstream channels may be transported in suspension while wash load may deposit in downstream sections due to reduced flow strength.

Settling velocity

The delivery of sediments to pores in the bed material by sedimentation is one important process of sediment infiltration and accumulation in river beds (Sear et al., 2008). Therefore, a proper definition of the settling velocity is essential for evaluating interstitial sediment dynamics. The terminal settling velocity is a key variable for studies on sediment transport as it defines the final velocity of a single particle in a fluid under gravity force. The settling velocity is determined by the particle size, shape and surface as well as the specific weight, viscous properties and concentration. During the settling process particles are exposed to gravitational forces expressed by the specific weight and drag forces that can be split into skin drag (tangential shear stress of the fluid) and form drag (pressure difference). For the terminal stage the drag and gravity forces should be equal (Wu, 2007). The developed formulas to determine settling velocities have begun with formulas for spherical particles, than have advanced for natural sediment particles (non-spherical), up to formulas considering hindered settling with presence of other particles. The probably most famous formula is Stokes law developed in 1851. Stokes law is valid for idealized spherical particles in laminar flow, and is presented in Eq.A.2.1.

$$\omega_s = \frac{gd^2(\rho_S - \rho_W)}{18 \cdot \mu} \qquad \text{Eq.A.2.1}$$

Because idealized spherical particles are rare in nature, subsequent research has shown that the shape of a particle can be a key variable for settling velocity. Firstly, the Corey shape factor have been introduced by Komar & Reimars (1978), and more recently Cheng (1997) and Jiménez & Madsen (2003) have improved relations between particle shape and settling behaviour. Nowadays many formulas for natural sediment are available and Wu & Wang (2006) tested ten different formulas and found that the formulas of Zhang (1961), Dietrich (1982), Cheng (1997), Ahrens (2002) and Wu & Wang (2006) give comparable reliabilities for predicting settling velocities for worn sediment particles.

Experiments have shown that in the presence of other particles the settling velocity is strongly reduced (Lewis et al., 1949). This hindered settling is mainly caused by the returning current induced by the settling sediments. Empirical formulas considering this decrease in sedimentation rate were developed by Richardson & Zaki (1954) or Teakle & Nielsen (2003). Cohesive processes like flocculation further influence the settling velocity but are not described here as this thesis is focused on non-cohesive material.

Incipient motion of sediments

For a number of sediment engineering and environmental problems in rivers it is fundamental to know about the conditions under which sediment particles begin to move. However given the numerous parameters that set particles in motion it is difficult to derive an exact deterministic definition (Bechteler, 2008). Generally different criteria for incipient motion can be considered, for instances single particle moving, several particles moving, or the general motion of the river bed. Another aspect is the distinction between uniform and non-uniform grain size distributions considering the hiding/exposure of particles.

Incipient motion of uniform sediments

There are four major forces that act on a single sediment particle: the drag and lift forces arising from the hydrodynamic forces, the gravity force acting vertically downwards and the reaction forces from surrounding sediment particles. If flow strength exceeds the gravitational and reactive forces a particle is set into motion. Nevertheless, as hydrodynamic forces (e.g. turbulences) as well as the reactive forces (e.g. positions of particles in a sediment bed) both vary in time, there is no precise flow condition that separates sediment motion from non-motion (Bettes, 2008). For uniform sediments several criteria are used to define a threshold for incipient motion. The most important ones are critical velocity and critical shear stress (Yang, 2006; Wu, 2007), while other criteria can be derived from both such as critical water depth, critical slope, or critical discharge (Bechteler, 2008).

Critical velocity

Given to the difficulty in measuring shear stress directly, a relationship between flow velocity and particle size to define a threshold for incipient motion is desired. But because flow velocity varies over depth and depends on hydraulic roughness, several critical velocities are possible for the same particle size (Bettes, 2008). Thus, although it might be useful for practical application the concept of critical velocities should be considered with caution. Relationships were first derived in a graphical representation of Hjulstrom (1935) defining velocities for erosion, transportation and sedimentation. Formulas to calculate the critical flow velocity were developed by Neill (1967), Yang (1973) and Zanke (2002). The latter gives similar value to those measured by Hjulstrom and is presented in Eq.A.2.2 where c_1 defines the lower (c_1=1.5) and upper limit (c_1=2.8) and c_2 is a coefficient for cohesive material.

$$v_{cr} = c_1 \cdot \left(\sqrt{(\rho_S - \rho_W) \cdot g \cdot d} + 5.25 \frac{\nu}{d} c_2 \right) \qquad \text{Eq.A.2.2}$$

Critical shear stress

According to many authors (e.g. Yalin, 1977; Bettes, 2008) the most rational approach for incipient motion is based on the critical shear stress. The shear stress as a function of the flow is related to the movement of sediment particles and hence, when a critical shear stress is reached it initiates particle motion. The most famous approach regarding the incipient motion is the Shields diagram (1936), using the dimensionless Shields number θ (also known as the solid Froude number Fr*) over the solid Reynolds number Re*. The Shields number depends on the critical shear stress, the difference in density between sediment and fluid, the particle diameter, and the gravity as it is shown in Eq.A.2.3.

$$\theta_{cr} = Fr_{cr}^{*} = \frac{\tau_{cr}}{(\rho_S - \rho_W) \cdot g \cdot d} \qquad \text{Eq.A.2.3}$$

However the original Shields curve was modified by several authors (e.g. Yalin & Karahan, 1979; Raudkivi, 1982; Zanke, 1990) mostly due to the lack of measurements for small solid Reynolds numbers and the neglect of lift forces.

Fig.A.2.2 presents the Shields diagram after Raudkivi (1982).

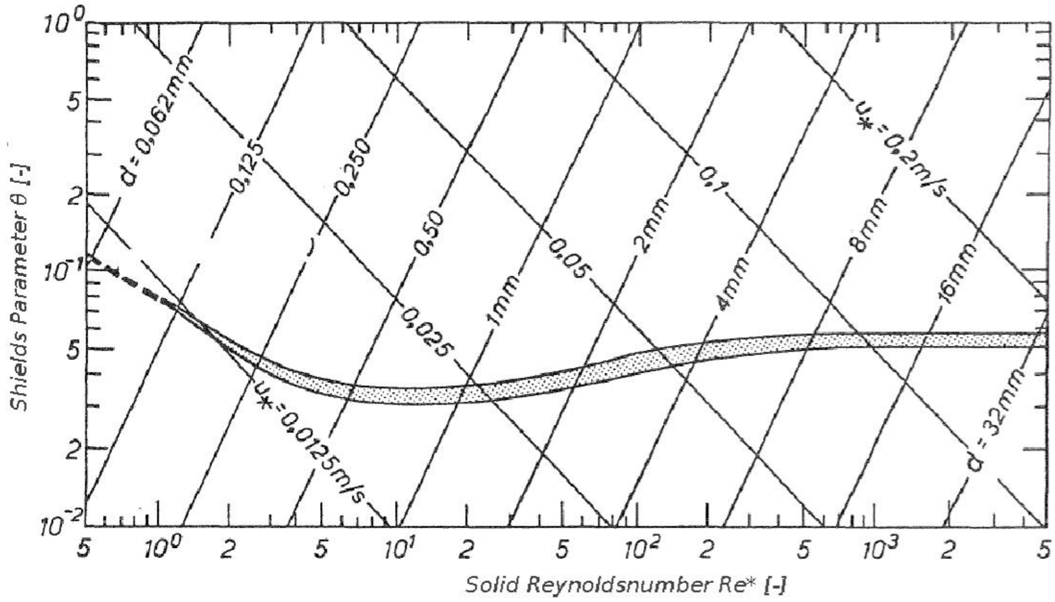


Figure A.2.2: Shields diagram (after Raudkivi, 1982)

Beginning with small Reynolds numbers the dimensionless shear stress is declining to a minimum at about Re*<10 considering that grains are protected by the enclosing laminar sublayer and being strongly bounded by electrochemical forces. As Re* increases (Re* approx. 10) the grain emerge from the laminar sublayer approaching the turbulence flow. The increasing grain size (silt/sand) is associated with weakening movements of all particle sizes and the Shields number achieves a minimum at 0.03. As Re* further increases (10<Re*<500) into the sand and gravel fraction, the Shields number increase from 0.03 to an asymptotic value of 0.06, that is valid for all higher values or Re*. In literature other critical values could be found e.g. $\theta_{cr} = 0.047$ as it was suggested by Meyer-Peter/Mueller (1948, Eq.A.2.4).

$$\theta_{cr} = 0.047 = \frac{\tau_{cr}}{(\rho_S - \rho_W) \cdot g \cdot d} \qquad \text{Eq.A.2.4}$$

Wu & Wang (1999) defined explicit relations between critical Shields number and dimensionless particle sizes (Eq.A.2.5/Eq.A.2.6):

$$\theta_{cr} = \begin{cases} 0.126 \cdot D_*^{-0.44} & D_* < 1.5 \\ 0.131 \cdot D_*^{-0.55}, & 1.5 \le D_* < 10 \\ 0.069 \cdot D_*^{-0.27} & 10 \le D_* < 20 \\ 0.017 \cdot D_*^{0.19} & 20 \le D_* < 40 \\ 0.012 \cdot D_*^{0.30} & 40 \le D_* < 150 \\ 0.052 & D_* \ge 150 \end{cases} \qquad \text{Eq.A.2.5}$$

$$D_* = d_m \cdot \left[\frac{\left(\frac{\rho_S}{\rho_W - 1}\right) \cdot g}{\nu^2}\right]^{1/3} \qquad \text{Eq.A.2.6}$$

Tables are available that provide recommendations for both critical shear stress and critical velocity (e.g. German Standard DIN 19661, Part 2).

Incipient motion of non-uniform sediment distributions (Hiding/Exposure)

Non-uniform sediment mixtures are characterized by the interactions between different size classes. Coarse particles usually show a higher exposure to flow, while finer ones are more likely to be sheltered between the large particles. Therefore, when sediment mixtures are exhibiting these two heterogeneous characteristics (e.g. $d_{84}/d_{16} > 1.5$, Bettes, 2008) these hiding/exposure mechanisms have to be considered when working with non-uniform sediment-transport. In literature correction factors for the existing formulas for incipient motion and transport are introduced. Ferguson et al. (1989) proposed a simple hiding function for the Shields relationship. For particle sizes smaller than the median grain size the Shields number is increased, while for particle sizes larger than the median grain size the Shields number is reduced. This tends to equalise shear stress and is known as equi-mobility (Bettes, 2008). Other formulas have been developed from Egiazaroff (1965) and Parker et al. (1982) using correction factors as functions of the non-dimensional sediment size. Wu et al. (2000) derived a formula to consider the probability for spherical grains to be exposed or hidden and defines a correction factor based on these probabilities (Chapter C.1.2.1). However, in natural rivers there might be many other factors influencing the initiation of sediment movement such as biological stabilisation, dunes, waves, cohesive or crushed material (Bechteler, 2008).

Bed load transport

Bed load transport refers to the quantity of sediments that are transported within a thin layer of a thickness of only few grain diameters and can be measured in volume, mass or weight. Typically, the amount of bed load in regards to total sediment load is relatively low, ranging between 5-20%, as bed load is transported discontinuously with occurring hydrological events while during low flow no material is transported as bed load.

During the last century numerous bed load transport equations have been developed using different approaches. Nevertheless, no sediment transport formula has been published that has achieved universal acceptance. Even under controlled laboratory conditions different equations give enormous discrepancies between calculated and observed datasets. This indicates that even after many years of research, the understanding and knowledge of sediment transport processes have not yet been developed enough (Hamilton et al., 2001). The interrelations among bed forms, roughness, abrasion, vegetation, sorting, hydraulic and sediment transport capacities depend on numerous parameters causing a high degree of complexity of the physical phenomena and are often subject to semi-empirical or empirical treatments obtained by simplified cases (Khorram & Ergil, 2010).

Going back to (1950) the work of Einstein can be considered as a milestone of modern sediment transport mechanics. Einstein provided the first theoretical framework (Eq.A.2.7) for sediment transport calculations by considering fluctuating hydrodynamic forces in his equation of dimensionless bed load intensity based on specific density, gravity, particle diameter and bed load rate (Garcìa, 2008).

$$\Phi = \frac{q_B}{\sqrt{\left(\frac{\rho_S - \rho_W}{\rho_W}\right) \cdot g \cdot {d_m}^3}} \qquad \text{Eq.A.2.7}$$

This dimensionless form of bed load intensity is found in many of the following approaches for bed load transport. According to García (2008) bed load transport functions are based on three main principle approaches, encompassing shear stress, energy balance and probability that are briefly explained in the following paragraphs:

Shear Stress:

This approach assumes that bed load transport varies directly with the difference between the shear stress acting on bed particles and the critical shear stress for incipient motion. The challenge within this approach is to define the effective bed shear stress that have to be equal to bed form drag that differs from the grain roughness and total bed shear stress. Exemplary equations using the shear stress approach are Meyer-Peter/Mueller (1948), Graf & Acaroglu (1968), Hunziker (1998) or Wu et al. (2000).

Energy Balance:

This approach includes equations based on the stream power or unit stream power concept. It considers the energy carried by the flow and the required energy to carry sediment particles. It balances the forces acting on a grain which are expressed as the product of bed shear stress and average flow velocity (stream power) or as the product of average velocity and channel gradient (unit stream power). Examples are the equations from Bagnold (1966) and Yang (1984).

Probability:

Probabilistic approaches relate bed load transport to turbulent flow fluctuations acting on sediment particles. The motion of particles depends on the probability that on a certain time and location the forces for mobility are greater than the resisting forces. Examples are the formulas of Einstein (1950) or Yalin (1972).

This wide range of different equations using various dimensional and non-dimensional parameters and the fact that each equation has its own range of applicability create confusion among researches when they have to select the best representative equation for a specific river. A number of studies have been published comparing bed load transport equations with observed data (e.g. Ribberink et al., 2002; Khorram & Ergil, 2010), the overall result is that researchers and engineers have to select equations that are appropriate for the specific cases given to the many constraints for each equation.

Khorram & Ergil (2010) examined the governing parameters for bed load transport for sandy and gravel bed-rivers. According to their study the most important parameters for sediment transport in gravel bed rivers are particle diameter, slope, shear stress, shear velocity and settling velocity.

Suspended load transport

Usually suspended load material is carried with flowing water over long distances as the particles are maintained with the mass of fluid by turbulent agitation without touching the bed. Suspended loads are typically given in the form of a sediment concentration (mass or volume). The solids in suspension account for 80 - 95 % of total sediment load but can show substantial variations. Next to hydrological events, land use and agriculture in the catchment are major factors contributing to the amount of suspended load.

Vertical distribution of suspended load transport:

Transport of suspended load is a combination of advective turbulent diffusion and convection. The advective diffusion defines the mixing of particles in the water column superimposed by the longitudinal flow. If suspended particles are heavier than water, the turbulent diffusion initiates a higher sediment concentration in near bed layers and a lower concentration on near surface layers. Convective transport occurs when the length of turbulent mixing is large compared to the sediment distribution length scale and might be described as the entrainment of sediment by large scale vortices (e.g. bed drops, hydraulic jumps). For the vertical distribution of sediment concentration in rivers the diffusion coefficient is often assumed to be proportional to the eddy viscosity of turbulent flow and can be derived from the parabolic diffusivity law (Chanson, 2004). Eq.A.2.8 gives the formula for the vertical distribution of sediment concentrations c_s, firstly developed by Rouse (1937), where δ is the reference level near the bed and $c_{S\delta}$ the sediment concentration at δ and κ the Karman constant (κ =0.4 in clear water).

$$\frac{c_S}{c_{S\delta}} = \left(\frac{h/_{z_S} - 1}{h/_{\delta} - 1}\right)^{\frac{\omega_S}{\kappa v_{cr}}} \qquad \text{Eq.A.2.8}$$

Typically the reference level δ is near the river bed and the concentration at level δ is assumed to be equal to the bed load concentration. The exponent in Eq.A.2.8 is also called the Rouse number. Physically the Rouse number expresses the effect of gravity against turbulent diffusion. For high Rouse numbers the effect of gravity is stronger and the vertical distribution of sediment concentration is less uniform and vice versa. Other approaches substitute the reference conditions by flux boundaries (Sanford & Halka, 1993), or using exponential (Kachel & Smith, 1989) or stratification-modified forms (Smith & McLean, 1977) of eddy diffusivity.

Near-bed concentration of suspended load

Suspended load functions for the near-bed concentrations can mainly be distinguished regarding the reference level. Einstein (1950) and Zyserman-Fredsoe (1994) set the reference level at two mean particle diameters above the river bed while van Rijn (1984) set the reference level at the equivalent roughness height or half of the bed form height. This makes it difficult to compare these equations. According to Wu (2007) the reference level should be at the interface between the bed load and suspended load layers. Another issue is that the suspended load near the river bed is difficult to measure and has to be extrapolated from measurements in the upper flow layer by assuming a vertical distribution of sediment concentrations. Thus the suspended load highly depends on the applied distribution function, which is often the Rouse distribution which is not reliable near the river bed as it assumes a horizontal uniformity and does not account for spatial variability of flow and bed characteristics (Orton & Kineke, 2001). Other formulas following the near-bed concentration approach are Engelund & Fredsoe (1976), Celik & Rodi (1988), Garcia & Parker (1991) or Hu & Wang (1999).

Suspended load rates

To obtain suspended load rates a common approach is the integration of the products of sediment concentrations and the associated flow velocity over water depth as it was firstly proposed by Einstein (1950) and as it is illustrated in Fig.A.2.3.

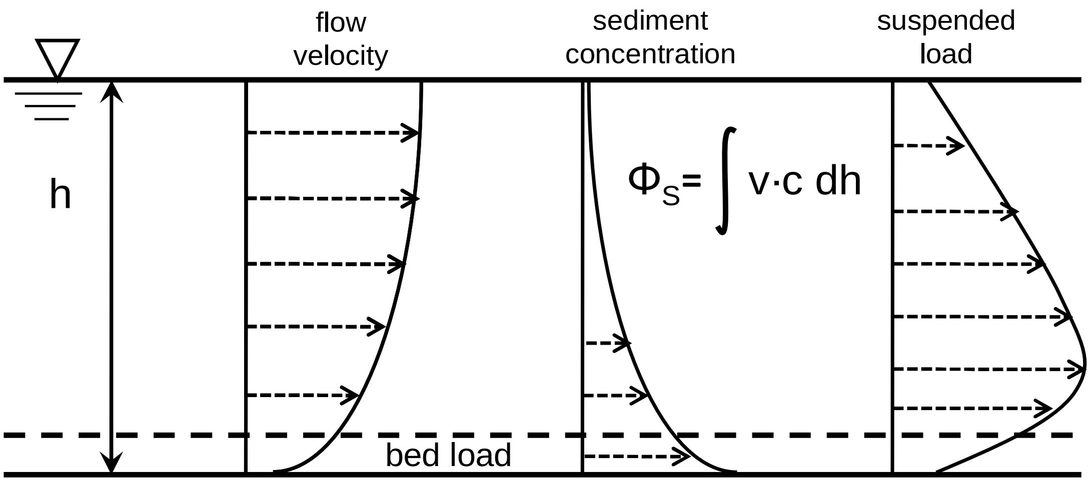


Figure A.2.3: Definition of suspended load transport (after van Rijn, 1993)

Other equations calculating suspended load rates can be categorized into the same basic principles as the bed load functions. Bagnold (1966) established a formula based on the stream power concept that was advanced by Wu et al. (2000) relating the suspended load rates to available energy rates in rivers and to the resistance to sediment suspension including multiple-sized effects. Zhang (1961) derived a relationship between suspended load capacity and a parameter defining the ratio of flow velocity to the product of gravity and settling velocity.

Total load transport

The total load transport can be classified in total transport rates and fractional transport rates. The separate functions were discussed in the preceding sections. Formulas that calculate total transport rates directly include Toffaleti (1968), Engelund & Hansen (1969), Ackers & White (1973), Yang (1973) and Yang & Lim (2003), while approaches for fractional transport rates are given by Proffitt & Sutherland (1983) and Karim (1998). As no total load transport is applied in this thesis these formulas are not described in detail. It should be noted that when comparing bed load and total load transport functions in terms of single or multiple particle sizes, the results show that multi-fractional formulas result in higher discrepancies than single-fraction formulas. Wu (2007) explained this by the existing interactions among different particle size classes in non-uniform bed materials and the difficulty to ensure that all size classes are at equilibrium states during measurements.

A.2.1.4 Embeddedness, colmation and clogging processes

Embeddedness, colmation and clogging are all terms that are commonly used in literature to describe sediment deposition, infiltration and accumulation of organic and inorganic fine material in gravel river beds with a consequently reduction of pore space and permeability in the river bed. The deposition/infiltration into the interstitial and the entrainment of fine sediment is a characteristic natural element of fluvial systems and one of the most complicated morphodynamic processes which is strongly coupled to the variability of the flow-sediment regime and on hyporheic exchange processes. As it has a detrimental impact on reproduction success of gravel-spawning fish (e.g. Sylte & Fischenich, 2002; Sennat et al., 2006; Sear et al., 2008; Scheurer et al., 2009) it is an essential topic in this work and a thorough knowledge about the ongoing processes and involved parameters is required. Although the importance is reported in many studies, no universal definitions and no delineation criteria are available to differentiate between embeddedness, colmation and clogging. Therefore, firstly a differentiation of the terms is done.

Differentiation and terminology

Next to the terms embeddedness, colmation and clogging, many authors distinguish additionally between physical, biological and chemical colmation (Baveye et al., 1998). Further, mistranslations might also lead to confusion as terms like inner/outer embeddedness and internal/external colmation are found in literature describing the work of Beyer & Banscher (1975). To further complicate the matter, the terms embeddedness, colmation and clogging are often used interchangeably in scientific literature. To differentiate among the available terms Tab.A.2.2 provides an overview of applied terms with brief descriptions.

Table A.2.2: Overview and description of various terms for embeddedness, colmation and clogging

term	location	description/definition	reference
embeddedness	surface	"The degree to which coarser particles are surrounded or covered by fine material."	Platt et al. 1983 Fitzpatrick et al. 1998
outer embeddedness	surface	"The fine material is larger than the pore space of the gravel-matrix of the river bed and is deposited on the surface layer."	Gutknecht et al. 1998
inner embeddedness	subsurface	"Deposition of suspended load in the pore spaces of the gravel-matrix of the river bed with reduction of pore space in the subsurface layer"	Schaelchli, 2002
colmation/clogging	surface subsurface	"All processes that lead to a reduction of pore volume, consolidation of the sediment matrix, and a decrease in permeability of the stream bed"	Brunke & Gonser, 1997
physical colmation/clogging	surface subsurface	"Fine sediment deposition, accumulation and infiltration into streambed sediments"	Descloux et al. 2010
biological colmation/clogging	surface subsurface	"Microbial activity lead to interstitial biofilms with adhesive capacities that reduces the transects of pores"	Beyer & Banscher 1975
chemical colmation/clogging	subsurface	"Iron clogging, redox potentials, ion exchange, flocculation change the geometry of the pore canals by disaggregation, dispersion or swelling"	Schwarz, 2003

The term embeddedness was introduced by Klamt in 1976 and originates from fisheries biology to quantify the amount of fine sediments in the rivers (Bunte & Abt, 2001). According to Tab.A.2.2 embeddedness refers mostly to the surface layer and focuses on the physical sedimentary process, while colmation/clogging includes additionally biological and chemical processes and extends the occurrence of colmation to the subsurface layer of river beds. This might have its origin as both terms colmation and clogging, are mainly published in hydrogeological literature dealing with the exchange processes between groundwater and surface water through the hyporheic interstitial. Tab.A.2.2 also shows that overlapping information is given, for instance the term inner embeddedness can be used as a synonym for physical colmation/clogging. Descloux et al. (2010) describes the term surface colmation similarly to the term for embeddedness. Outer embeddedness is a very unstable condition and only occurs when the fine sediments are larger than the pores of the gravel-matrix and the hydrodynamic forces are too small to transport the fine sediments further downstream (Beyer & Banscher, 1975; Gutknecht et al., 1998). In Fig.A.2.4 four different kinds of colmation are illustrated:

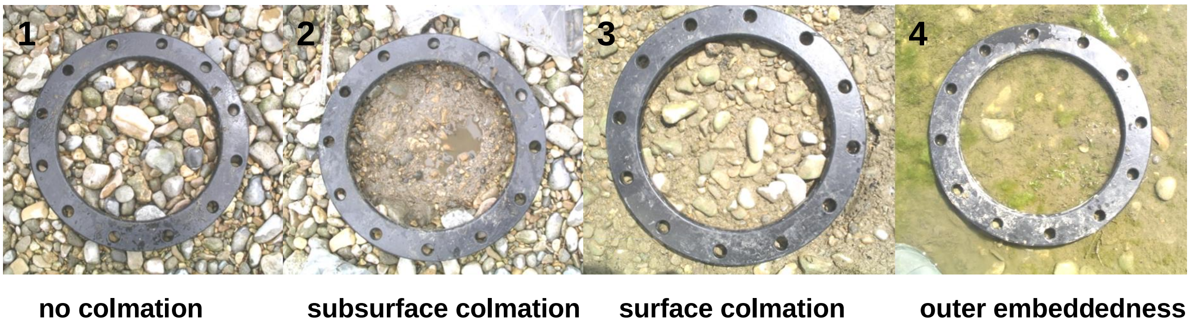


Figure A.2.4: Exemplary images of different colmation types (photos by Eastman, 2004)

The first picture on the left hand side of Fig.A.2.4 shows an unclogged river bed with high permeability and large pores while the second one illustrates a colmated subsurface layer that becomes visible when the surface layer is removed. The third photograph shows a surface colmation or embedded surface layer and the last one pictures outer embeddedness with deposition of fine particles on the riverbed.

In this thesis the term colmation is defined as an integrative parameter considering sedimentary colmation in the form of organic and inorganic sediment infiltration but also biological and chemical colmation due to biogeochemical processes in surface and subsurface sediment layers. Further, the term physical colmation is used for describing the infiltration and accumulation of inorganic fine sediments in the interstitials of the river bed.

Processes and parameter

Gradual physical colmation is a natural highly dynamic process of fluvial river systems and occurs typically during low flow situations when particles transported in the suspended load can deposit and infiltrate into the gravel-matrix of river beds (Brunke & Gosner, 1997). In dynamic, active rivers with frequent peak flows the interstices of a clogged river bed can be reopened so that the deposited fines are resuspended and flushed further downstream (Schaelchli, 1992). This process is called decolmation and the degree of sediment remixing between surface and subsurface particles depends on the erosion potential of the peak flow. The balance between physical colmation and decolmation can be disturbed significantly by anthropogenic activities like agriculture, deforestation, mining or alterations of the flow and sediment regime (Hancock, 2002; Baker et al., 2010). While land use practices like extensive agriculture or deforestation lead to an unnatural increase of fine sediment input, dam construction, impoundments or embankments lead to encroachments of natural hydromorphodynamic processes like suppression of peak flows or bed load deficits that are important for decolmation processes.

The evolution of a colmation layer is determined by a high number of spatial and temporal varying factors that encompass hydrologic, geohydrologic, hydraulic, morphologic and biogeochemical features resulting in a complex system of interactions.

Fig.A.2.5 gives an overview of parameters and processes influencing colmation:

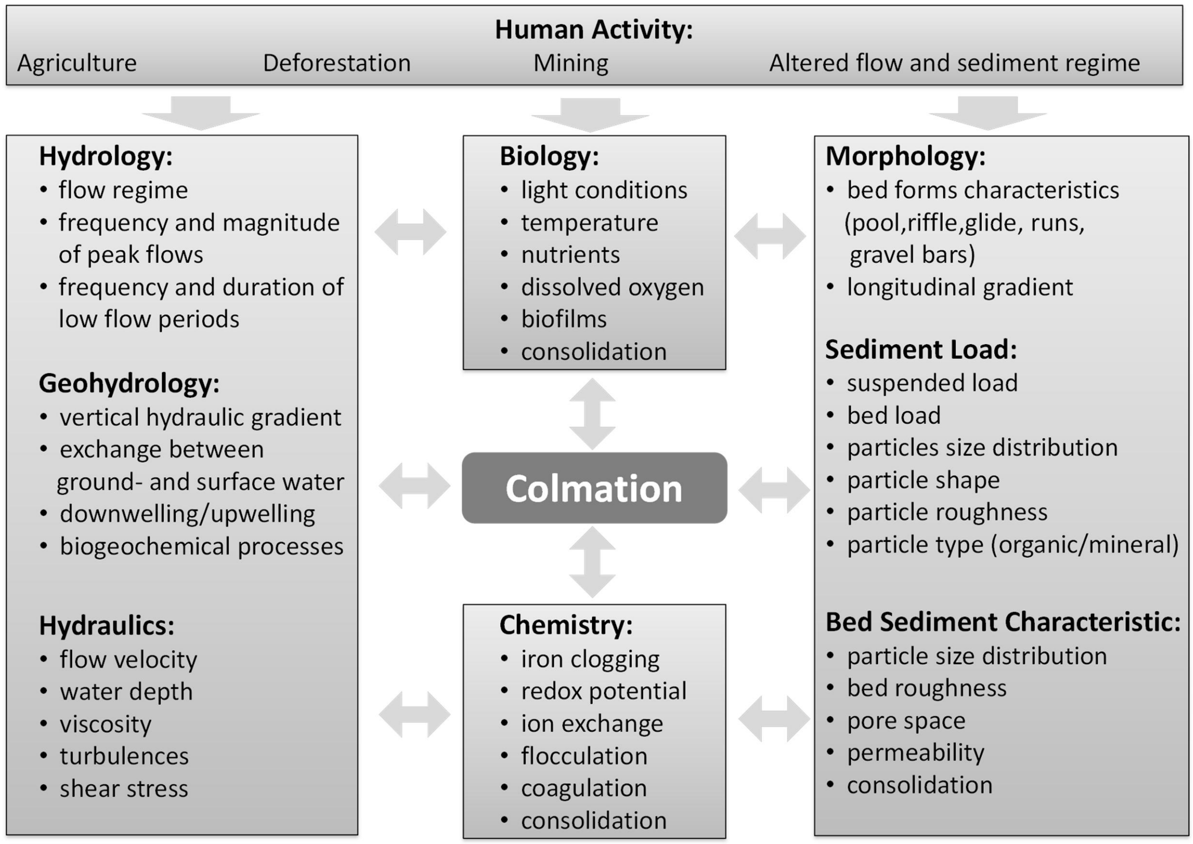


Figure A.2.5: Factors and processes influencing the colmation process

Although biological and chemical processes can have s strong influence on the consolidation and clogging of river beds the primary focus of this thesis is on physical colmation induced by sediment infiltration processes while biological and chemical colmation are not directly addressed but approximated by an indicator describing the hyporheic variability. The mechanisms that induce physical colmation are not totally understood but generally the depth of penetration and vertical distribution depends on multiple interactions between the vertical hydraulic gradient, suspended and bed load, particle size and shape (Schaelchli, 1993; Descloux et al., 2010) as well as lateral sediment-transport processes in-between the interstitials (Sear et al., 2008). Moreover, overlapping scale-effects ranging from large-scales processes such as flow regime, groundwater flow paths or geomorphologic characteristics to meso- and micro-scaled processes such as particle size distribution, sediment load or infiltration mechanisms support the complexity and the comprehensibility of colmation processes. However on a local scale sediment infiltration and accumulation in the pore spaces of the riverbed can be considered as the governing process of physical colmation (Seydell et al., 2009) which is described in detail in Chapter A.2.3.2.

A.2.2 Fluvial ecological processes

Ecosystems are composed of physical, biological and chemical components. The natural dynamics of processes and interactions within these components characterise them in terms of both their functionality and services provided to human society. In order to assess the ecological status of fluvial ecosystems it is essential to understand the nature and value of ecological processes along a river on appropriate scales and to work with appropriate indicators reflecting the impacts of in- or external stressors.

A.2.2.1 Fundamentals in river ecology

An ecosystem is the basic functional unit in ecology as it includes biotic organisms and their abiotic environment. Traditionally, the abiotic and non-living components of ecosystems can be classified as water, air, soil and light while biotic and living components are grouped in producers, consumers and decomposers. The two major ecological processes are energy and material flows interacting in numerous and complex ways (NRC, 2000). In river ecology the abiotic attributes can be subdivided in physical factors, chemical factors and nutrients, while biotic attributes are organized on individual, population or community levels (Poff & Ward, 1989; Smith, 2002). The flow chart in Fig.A.2.6 gives an impression of the complex interactions between abiotic and biotic factors, processes and their influence on habitats for aquatic species.

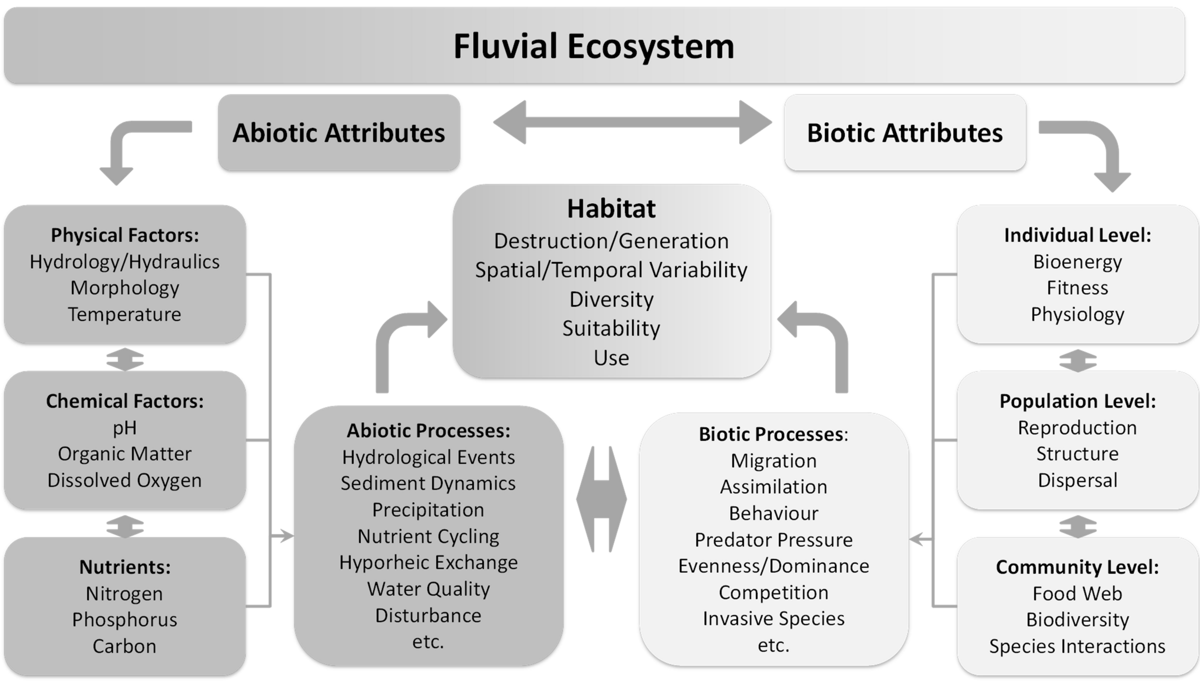


Figure A.2.6: Ecological attributes and processes in fluvial ecosystems

A fundamental consequence of fluvial ecosystems functions is the spatial and temporal variability of various habitats types: a habitat is defined as the environmental surrounding that is composed of multiple dimensions representing biotic and abiotic components and their characteristics (dynamic and static) that are directly or indirectly related to the use of a location by an organism (Beyer et al., 2010). This definition implies that habitats are the base of life for instream biota (Jowett et al., 1997) featuring both abiotic and biotic attributes. This habitat related view of ecology is warrantable given to the dominating role of habitats in fluvial ecosystems as long as habitats are not considered as isolated sections or locations neglecting critical, functional linkages among habitats and subsets of biota (Helfman et al., 2009). A major advantage of the habitat-centred view is that the physical characteristic of habitats can often be described and quantified in detail as profound knowledge about physical processes is available compared to biological processes (Jørgensen & Bendoricchio, 2001).

The physical factors comprise also variables describing hydromorphodynamic processes such as flow variations, sediment supply, transport of sediments, particle size distribution and includes additionally thermal and other energy transformations. Chemical factors are mainly concentrations of suspended or dissolved substances that are naturally present in rivers, such as oxygen, inorganic/organic matter, ions etc. Further, nutrients are required for necessary life functions to sustain itself and other forms of life and can be a limiting factor if demand exceeds availability (Allen & Castillo, 2007). The most utilized nutrients in fluvial ecosystems are nitrogen, phosphorus and carbon. Especially the balance between carbon (as the energy currency) and nitrogen (as the nutrient currency) is a key parameter (C/N-ratio) in determining the productivity of ecosystems (Young & Sanzone, 2002). A wide range of fluvial dynamic abiotic processes are responsible for the creation, destruction and maintenance of habitat templates which might influence behavioural, physiological and life-history characteristics of a species (Poff & Ward, 1990). Especially the dynamic nature of the abiotic attributes is of crucial importance for ecosystems functionality. The natural flow paradigm of Poff et al. (1997) describes five critical components in terms of hydrological variation (magnitude, frequency, duration, timing and rate of change) that influence the variability and heterogeneity of habitat structures in rivers (Richter et al., 1997). Hydrological and geomorphic processes are closely related in fluvial ecosystems over longitudinal, lateral and vertical dimensions and the dynamic structuring of habitats involves numerous morphodynamic processes that are driven by hydrological events (see Chapter A.2.1.1). These events or disturbances might be defined as any event that disrupt abiotic or biotic processes in ecosystems by changing the physical-chemical environment, resources or community structures in a large area or for a long time period (Stanley, et al. 2010). Large disturbances might even result in a complete re-structuring of an ecosystem, creating a template upon subsequent ecological processes and interactions among species occur (Young & Sanzone, 2002). Organisms may be adapted to frequent or large disturbances and also depend on the recurrent changes of the ecological environment. All abiotic attributes generally interacts with each other and affect ecosystems and habitats by single or combined processes that describe typical patterns of circulation, mixing and dispersion of energy and mass (Jørgensen & Bendoricchio, 2001).

Biotic attributes in ecosystems are identified with characteristic levels of ecological organisation (Smith, 2002). On the individual level the physiological status of an organism is of interest in terms of its fitness, metabolism and other bioenergetic processes. For example in fisheries the mass to length ratio is often used as a parameter of the individual condition (Jones et al., 1999). Sign of disease is another factor to describe the individual status that might change the typical behaviour, size and mass of individuals. On the population level the size of a population, the demographic structure (age and composition of population) and dispersal are key measures of population health. Combined with information about the frequency of natural reproduction these factors can be used to estimate the population viability (Young & Sanzone, 2002). An ecological community or biocoenosis is an assemblage of species/populations that occupy the same geographical area and are tied together by similar environmental features. On this level the spatial extension, composition (commonness/rarity), species diversity as well as the trophic structure that include the food web complexity are major parameters of biotic integrity (Karr, 1993).

The use of available physical habitats for different purposes might depend on interactions between the biotic attributes on different ecological levels or can simply be a reflection of physiologically optimal environment or both of them (Helfman et al., 2009). Among the most important species interactions are competition, predation and dominance. In general, species compete for habitats in terms of food, feeding, resting sites or refuges from predators or disturbances. Predator-prey interactions have direct or indirect effects on prey population size. Direct effects are mortality while indirect effects are habitat shifts due to a predator's presence, forcing potential prey to use suboptimal habitats which in turn can affect individual growth and fitness (Helfman et al., 2009). Dominance behaviour is driven by size, sex, age and previous experience and in general larger organisms dominate over smaller, older over younger and residents over intruders. In terms of habitat use the dominant fish usually occupy the most favourable habitat expelling subordinating individuals to suboptimal sites. Consequently dominant individuals have higher feeding rates, faster growth and higher fitness (Bachman, 1984). Individual behaviour and habitat choice is also a function of temporal cycles. For example a daily, biweekly, lunar or seasonal pattern of species activity is related to foraging, migration and reproduction. Another biotic aspect concerns invasive species. In natural conditions species are constrained by co-evolutionary processes. If invasive fish are introduced, the co-evolutionary processes are disturbed leading to homogenization of previously unique assemblages and may result in population reductions or the extermination of native species, directly through predation or indirectly through superior competition (Helfman et al., 2009).

This brief overview emphasizes the complexity and dynamic nature of ecosystem processes and elucidates the challenge of assessing the ecological status of rivers as well as the challenging requirements of approaches, methods or modelling tools to do such an assessment. According to Egger et al. (2005) the aggregation of abiotic and biotic attributes is a fundamental precondition to allow comprehensible assessments regarding impacts on fluvial ecosystems.

A.2.2.2 Functions and services of fluvial ecosystems

A developing trend in environmental and ecological research emphasizes the functions and services of aquatic ecosystems including the evaluation of abiotic and biotic attributes related to the natural dynamic functioning of rivers to gain a deeper understanding of the complex processes in ecosystems. The term 'ecosystem function' dates back to the work of King in 1966 and generally is defined as 'all natural physical, chemical and biological processes or properties that contribute to the self-maintenance of an ecosystem', while 'ecosystem service' refers to the 'quantifiable and qualitative benefits of ecosystem functioning to human society.'

DeGroot et al. (2000) found that given the wide range of ecosystem functions and services, it is convenient to group them in four primary categories (regulation, habitat, production and information). It is the combination of these different functions, products and attributes that makes ecosystems valuable for flora and fauna, including human society (Bergkamp et al., 2000). The main aquatic ecosystem functions and services of fluvial ecosystems are listed below for each category:

Table A.2.3: Ecosystem functions and services of natural aquatic ecosystems (modified from DeGroot, 1992)

	ecosystem function	ecosystem service
regulation control of essential ecological processes and life-supporting systems	- quantity and quality of water and sediments - nutrient cycling - biogeochemical cycling - genetic diversity	- flood protection - drinking water - irrigation - cooling water
habitat refuge for flora and fauna in order to maintain biodiversity and evolutionary processes	- physical/chemical environment - habitat diversity - biological conservation - provision of refuge and reproduction habitat	- fish industry - species richness - aquaculture
production resources provided by natural ecosystems	- water, energy, food - biomass - genetic resources	- hydropower, energy - food (esp. fish) - industry
information opportunities for reflection and cognitive development	- attractive landscape - natural variety - cultural variety - biomass	- recreation - fishing, water sport - experience of untamed nature - inspiration (literature, music) - food (esp. fish)

The concept of ecological functions and services gained popularity in recent research as it helps to demonstrate the public, managers and governments their crucial ecological role (Thorp et al., 2010) and provide an important basis for communication purposes. DeGroot et al. (2002) evaluated the concept of ecosystem functions and services in terms of ecological, socio-cultural and economic values (Wilson & Howarth, 2002) concluding that one of the main problems is the overlapping of ecosystem functions and services as well as the interconnectedness of certain functions with associated services. According to Bouman et al. (2002) dynamic models are needed to account for the interdependencies between ecosystem functions, services and their values.

In this thesis the concept of ecological functions and services is relevant as habitats are explicitly named as a functional ecosystem group and thus underpins the importance of aquatic habitats for ecological processes. Especially the habitats for reproduction purposes are frequently mentioned in literature to maintain biological conservation (e.g. DeGroot et al., 2002, Bergkamp et al., 2000). Sustainable management of fluvial ecosystem and the assessment of goods and services require deep knowledge about the different occurring scales that are interlinked by longitudinal, lateral, vertical and temporal dynamics (Staes et al., 2008).

A.2.2.3 Ecological scales

In defining ecological scales it must be distinguished between biotic and abiotic scales. The ‘concept of biological organization levels’ (Barrett et al., 1997) is ordered hierarchically comprising genes, cells, organs, organisms, populations, communities and biospheres and is focused on the biotic aspects including all kind of ecosystems, while abiotic scales for riverine ecosystems are more orientated on the hierarchical scheme of fluvial systems and functional habitat units. The most famous hierarchical habitat classification system has been developed by Frissell et al. (1986). It is based on the assumption that biotic processes are determined by physical habitats. It ranges from stream systems to microhabitats and provides spatial and temporal scales at each hierarchical level. An extension to such hierarchical frameworks is the interdisciplinary framework of Thoms & Parsons (2002) which additionally considers multi-scale interactions among biota, physical structure and hydrology organized in key hierarchical links between hydrology, geomorphology and ecology as it is essential to know at what scale abiotic and biotic responses occur. The hierarchical structure implies the typical sensitivity and persistence time pattern with low sensitivity to disturbances and long time scales of persistence for the large scale and high sensitivity and short time scales on small scales.

In Fig.A.2.7 the multi-scale relationships between hydrology, geomorphology, habitat and ecology are illustrated including the abiotic and biotic responses due to changing environmental conditions in a river basin.

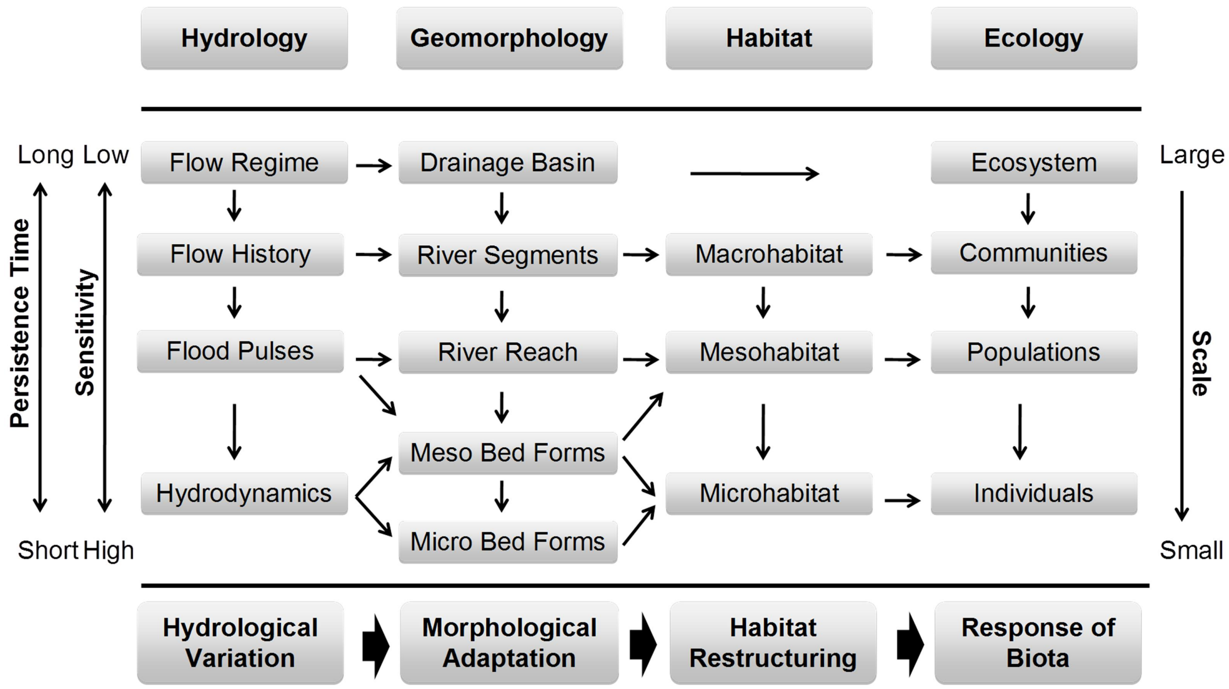


Figure A.2.7: Multi-scale relationships between hydrology, geomorphology, habitat and ecology in hierarchical organisation with abiotic and biotic response (modified from Thoms & Parsons, 2002)

The extension from discipline-specific frameworks to interdisciplinary frameworks allows to link varying environmental conditions with biotic response (Thoms & Parsons, 2002). On a microhabitat scale, characteristic hydrodynamic patterns influence the distribution and compositions of particle sizes which is affecting biota on an individual level. On the meso-scale the investigation of magnitude, frequency and duration of flood pulses affect the morphology of river reaches and eventually change meso-scaled bed forms like gravel bars or pool/riffle-systems. On meso-scale it is consequently more appropriate to monitor the biotic response of populations than that of single individuals.

A.2.2.4 Indicators for ecological integrity

Indicators are generally defined as signs or signals that relay complex messages in a simplified and useful manner. In terms of fluvial ecosystem this means, that the complexities of the ecosystem have to be captured by ecological indicators that reflect physical, chemical and biological factors to characterize the present ecological status and allow for the evaluation of ecological quality based on relationships between stressors and indicators. Further indicators need to remain simple enough to be routinely determined (Dale & Beyeler, 2001). The Environmental Protection Agency of the United States (Jackson et al., 2000) developed 15 guidelines for ecological indicators which can be further summarized into four main criteria:

Conceptual Relevance: the selected indicator has to be relevant to the assessment question as well as to the ecological function. This means it must be sensitive to stressors and respond to these stressors in a certain manner.

Feasibility of Implementation: the feasibility of an indicator depends on practicable aspects like cost, logistics and measurability.

Response Variability: the variability of an indicator response has to be understood to assign responses to stressors and to distinguish the 'true' response from other sources that might be responsible for response variability. Therefore it may not be appropriate to address all components of natural variability.

Interpretation and Utility: a useful indicator must produce comprehensible results that can be understood by scientists, managers and policy makers alike.

Selection of appropriate indicators to meet the above mentioned criteria is a key management goal and a challenging task given to the variety of stressors in fluvial systems (Walters et al., 2009). Species are commonly used as ecological indicators as their presence/absence or abundance can indicate the functioning and condition of an ecological system. According to Young & Sanzone (2002) indicator species are classified in keystone species, umbrella species or link species. Keystone species (top-predators, dominant herbivores) have a disproportionate influence on ecological processes and their distinction/introduction may have a cascading effect on other species (Power et al., 1996). Umbrella species have overlapping habitat requirements including those of many other species. This implies that the protection of an umbrella species simultaneously means to protect other species sharing the same habitat (Ozaki et al., 2006). Link species have a critical role for specific ecological processes, such as energy and material flux (Dale & Beyeler, 2001) and respond to single or multiple processes in fluvial ecosystems.

In fluvial ecological research a great number of indicator species have been utilized within river systems with a strong emphasis on phytoplankton, macrophytes, benthic invertebrates and fish (Bonada et al., 2006; Griffith et al., 2005) which are also the four organism groups addressed in the Water Framework Directive 2000. As this work is related to gravel-spawning fish only this indicator species is described in detail.

Fish have been used for many years to indicate overall river health and it is well known that long-term exposure to pollution cause detrimental impacts on fish health (Baron et al., 2002). Fish have relative long life histories and integrate the chemical, physical and biological history of waters. As fish are at the top end of the aquatic food web they often reflect responses of the entire trophic structure to environmental stresses. Next to the indication values in terms of water quality, fish are excellent indicators for habitat qualities at various spatial scales due to their complex ecological requirements during their life-cycles (Bayley & Li, 1996). As migratory organisms' fish movements take place longitudinally, laterally and vertically depending on species and migration purpose. Therefore the connectivity and spatial/temporal variations of habitats provided by a river is of major importance (Jungwirth et al., 2000). As habitats are determined by interaction of geomorphic and hydrologic variation fish serve additionally as indicator for morphodynamic processes in rivers and this clearly distinguish fish from other indicator species and underpins the significance as an essential indicator to assess ecological integrity (Schiemer, 2000).

The basic principle in applying ecological indicators is to assess the deviation of the current ecological situation from a natural system that is used as a reference condition (Reynoldson et al., 1997). In Schmutz et al. (2000) a reference condition is defined as ‘the continuance of all processes and attributes interacting with the environment in such a way that the biotic community corresponds to the natural state of the relevant aquatic habitat’. Thereby the undisturbed pristine system has to be comparable to that of the assessment system in terms of eco-region, hydrology and geomorphology (Muhar et al., 1993).

In this thesis the reproduction period of gravel-spawning fish is used as an indicator which responds highly sensitive to dynamic fluvial processes. To emphasize the high indication value to dynamic fluvial processes a detailed look at the processes and parameters to describe the reproduction habitat is required.

A.2.2.5 Reproduction of gravel-spawning fish

Reproduction is the link between generations and is the fundamental process to develop stable populations (Kamler, 1992). For gravel-spawning fish species the completion of the life cycle depends on habitat quality and the availability at all development stages during the reproduction period (Elliott, 1994).

Reproductive fish guilds

Kryzhanovsky (1948) was the first to propose a classification for different reproduction types for freshwater fish species in terms of spawning tactics and ecological niches. He defined five ecological groups based on the spawning substrate: lithophils (rock and gravel spawners), phytophils (plant spawners), psammophils (sand spawners), ostracophils (egg deposition inside mussels) and pelagophils (pelagic spawners). Based on these ecological groups Balon (1975, 1990) developed one of the most comprehensive classifications including 36 reproductive guilds reflecting evolutionary lines (Jakobsen et al., 2009). The 36 reproductive guilds are firstly grouped according to the parental care, the pattern of care of the eggs and in habitats as locations of egg deposits. Typical habitats for egg deposition are rocks, gravel, sand, mud, aquatic and terrestrial plants, mussels or simply the water column. Furthermore the parental care is subdivided in terms of non-guarders, guarders and bearers. This subsequent classification concerns different care patterns of the eggs. Open substratum egg scatterers are fish species that leave eggs after spawning in the free water zone or on any substrate, while brood hiders deposit eggs in inconspicuous places such as cave, rock, interstices or gravel depressions. Clutch tenders are non-nesters that guard their eggs in the water column or on different substrate types. Other examples are nesters which deposit eggs in nests, external brooders and internal live bearers. According to Balons classification (1975, 1990) most gravel-spawning fish species belong to brood-hiding lithophils.

Among the entire group of gravel-spawning fish salmonids, especially Atlantic salmon *(Salmo salar*) and brown trout (*Salmo trutta*) are of considerable economic, ecological and social importance in terms of aquaculture, stocking, fishing or as ecological indicator. Both fish species belong to the salmonids group and according to Groot (1996) no other taxa have been researched so extensively as this group.

The next section deals with the requirements of life-stages during the reproduction of brown trout. Presently some disagreement among fisheries researchers about how to distinguish between the development phases during the incubation period exists as changes in anatomy, physiology and behaviour have to be considered additionally next to significant endpoints like hatching or absorption of the yolk sac (Helfman et al., 2009).

In this thesis the reproduction is subdivided into the spawning period, the incubation period and emergence period, while the incubation period is further subdivided into the eyed-egg stage, hatching stage and larval stage. The following section contains detailed information about each stage during the reproduction period including descriptions of the most dominant processes and parameter. Thereby it is distinguished between controlling factors and habitat describing variables which might be applicable for habitat modelling.

Spawning Period

<u>Spawning Process</u>

Begin of spawning

Although there is a great variability between rivers and salmonid populations regarding the onset of spawning, it is generally assumed that the day length and temperature are the major drivers in regulating the start of spawning (Armstrong et al., 2003). Furthermore Klemetsen et al. (2003) found that spawning in northern latitudes is earlier given to the cold winter temperatures and have typically longer development time for the eggs. However next to these seasonal and environmental aspects the physiological readiness to spawn is also a key factor and when the right time approaches other factors may loose their significance (Crisp, 2000).

Selection and construction of spawning redds

The spawning act starts with searching unoccupied spaces in areas with suitable habitat conditions for spawning (Esteve, 2005). The female starts digging redds by beating the gravel with rapid thrusts of their tail but before the final locations are fixed the females digs exploratory over a fairly large area to probe for the best location. Once a redd site is selected redd construction starts with more vigorous tail movements in an upstream direction. Thereby sediment is loosened and lifted into the water column. Fine sediments are transported downstream (Quinn, 2005), while larger sediments (gravel) are transported upstream resulting in a depression, which is also called the pit where the eggs will be deposited (Crisp & Carling, 1989). During redd construction the females defend their redd locations from newly arriving females while the males do not contribute in redd digging but fight to gain access to the nesting females showing a typical dominance-driven behaviour (Groot, 1996).

Fertilization

The testing of the readiness of the redd by the fins of the females is a signal for the males that oviposition is approaching. To release the eggs both the female and male will go into a crouch position with the mouth agape (Briggs, 1953). This crouching behaviour will be repeated several times before the eggs are finally released. Simultaneously the male express a cloud of milt to fertilize the deposited eggs. Immediately after fertilization the female starts with the nest closing.

Redd closing

To cover the redd the female moves upstream to displace new sediments. The first digs intend to drive the eggs deeper into the gravel interstices and afterwards the eggs become covered with sediments by stronger digging movements where coarser sediments are carried downstream, covering the pit and building the tailspill. Finer sediments are again transported downstream beyond the limits of the redd (Kondolf & Wolman, 1993). The sequential pit excavation and tailspill development result in multiple egg pockets clustered in a teardrop shape that can easily be identified by its cleaned substrates, sorted particles sizes and the characteristic tailspill. Fig.A.2.8 gives a schematic illustration of constructing spawning redds of salmonids.

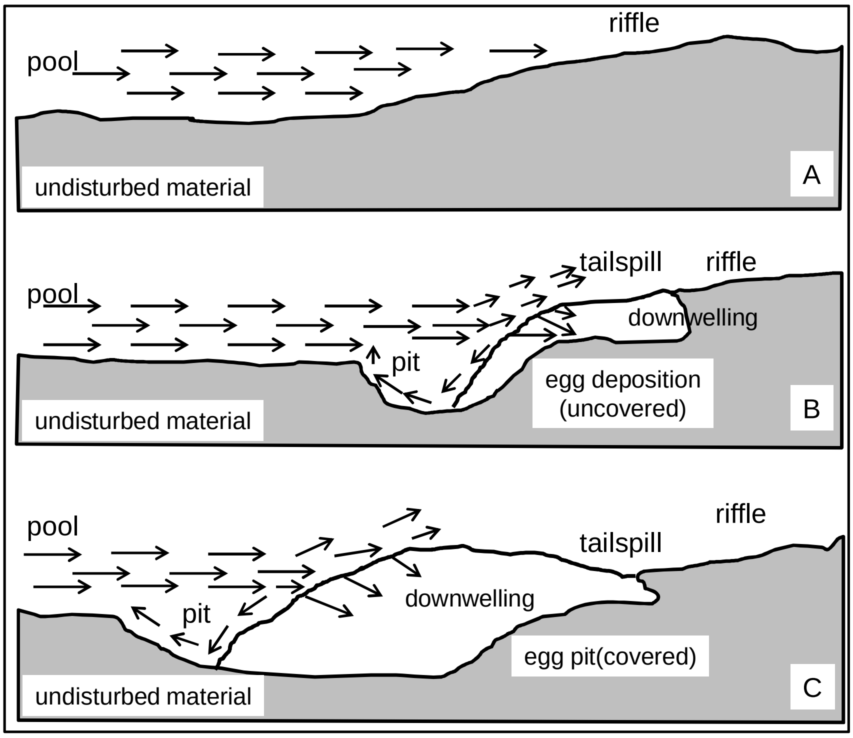


Figure A.2.8: Longitudinal sections of typical redd construction of salmonids. A shows the undisturbed pool-riffle-transition, B the excavation of the pit, and C the tailspill when closing the nest (modified after Bjornn & Reiser, 1991)

Spawning Habitat

Typical spawning grounds for salmonids are often found at the crest of a riffle or at the tail-out of a pool (Tonina & Buffington, 2009). The accessibility of spawning ground is a very important factor, especially for river management, but it is not considered here, as migration abilities are investigated on larger spatial scales. The following sections describe the controlling factors and processes during the spawning period.

Controlling factors and processes

The overall governing process in terms of suitable habitat conditions is the variability of flow and sediment-transport. The interactions between morphology and hydrology are the major drivers to create characteristic pool-riffle-sequences which provide spawning habitats. Therefore flow variability and related sediment-transport are often a prerequisite to create suitable spawning sediment conditions (Poff et al., 1997). The flow variability is required for regular bed alterations to provide a renewal of substrate conditions (Merz et al., 2004) by breaking armouring layers and flushing fine sediments out of the interstitial of the riverbed. To date, there is not much information available regarding the timing, magnitude and duration of flow variability to induce such morphodynamic processes. Pulg (2006) found regarding infiltration processes and the consequent reduction of pore space that unsuitable spawning conditions are achieved after about six to nine months in a subalpine river, and suggests that bed alterations should occur roughly twice a year. Areas with more disturbances seem also to be avoided by salmonids as during the incubation period as stable hydromorphodynamic conditions are required.

Habitat describing factors

It is widely known that spawning habitat is influenced by the standard habitat parameters water depth, flow velocity and sediment characteristics (e.g. Kondolf & Wolman, 1993). Other abiotic parameter comprise available space, consolidation of the bed substratum, surface and subsurface flow conditions and cover availability (e.g. Chambers et al., 1955; Schuett-Hames & Pleus, 1996).

Some of these factors are related to the physical ability of the female salmonids to successfully dig a spawning redd. A site might be rejected if sediment characteristics contain too large or heavy particles for a female to move, or are too consolidated to dislodge (surface colmation). Kondolf (2000) suggests that spawning fish can move gravel with a median diameter up to about 10% of their body length. Similarly a site is not suitable if the flow velocity is too strong to hold position or water depth is too shallow to manoeuvre.

Salmonid females select spawning grounds for another set of criteria dealing with subsurface characteristics that are driven by pressure gradients, in order to ensure favourable interstitial conditions for the incubation period. Typically these are downwelling areas where oxygen-rich surface water can enter the interstitial path ways to deliver the required dissolved oxygen to the eggs and larvae (Crisp & Carling, 1989). Even when water depth, flow velocity and sediment size appear suitable, a site can be avoided after test digging, presumably due to lack of suitable subsurface flow conditions (Schuett-Hames & Pleus, 1996).

A third type affecting spawning habitat is related to the safety and survival of the female during the spawning process. The availability of cover such as pools, overhanging vegetation, submerged vegetation, woody debris or undercut banks provides protection from predators during spawning (Zimmer & Power, 2006) and are preferred locations (Bjornn & Reiser, 1991).

The density of redds might be an additional factor influencing spawning habitat. The amount of required space depends mainly on body size and behaviour of the spawners and the area required per redd, but also on the quality of the spawning area. If spawning grounds are only moderately suitable it may force females to make several redds leading to an increased competition among the females (Bjornn & Reiser, 1991). Tab.A.2.4 summarizes the main factors and functions influencing spawning habitats of salmonids.

Table A.2.4: Summary of processes and factors influencing the habitat of salmonids for spawning

Factors	**Function**
Controlling factors and processes	
hydrologic and morphologic variability	frequency, magnitude, duration of events before spawning season, inter-annual bed alterations with sediment mixing, breaking of armoured layers, flushing fines out of the interstitial

Habitat describing factors

water depth	sufficient manoeuvrability for spawning process
flow velocity	maximum velocity to hold position over redds, minimum velocity for downstream transport of fines during digging
particle size distribution	portion of suitable grain sizes, portion of unsuitable grain sizes (fines+non-moveable fractions)
permeability	consolidation of surface layer (surface colmation), movable sediments for digging purposes
vertical hydraulic gradient	providing sufficient surface water infiltration
cover	shelter from predators/disturbances
space	fish behaviour, selection of most suitable spawning site, redd density, competition

Most variables in Tab.A.2.4 are characterized by a highly temporal and spatial variability reflecting the dynamic behaviour of rivers. Additional parameters that describe water and sediment quality in terms of chemical conditions such as the pH, salinity, pollution due to contaminants, etc are not considered here.

Incubation Period

Embryonic and larval development

“Green Eggs”

The incubation period utilizing the gravel interstices and hyporheic interstitial starts with the embryonic phase and commonly the freshly fertilized eggs are referred as the “green eggs”. Typical egg sizes of brown trout vary between 3 mm and 7 mm depending on fish length. One of the first processes in embryonic development is the water-hardening of eggs and occurs directly after fertilization. The eggs absorb water through its semi-permeable layer and start to swell becoming firm and slick to protect the internal developing embryo from mechanical shocks (Billard & Jensen, 1996). During the early development cell layers grow from the top of the egg and expand over the surface, enveloping more and more of the yolk mass. In this stage the egg is extremely fragile and highly sensitive to any mechanical shocks due to gravel movements. The eggs remain in this tender status until the black pigments inside the retina of the developing eye are deposited which indicates the transition to the next development stage called “eyed-eggs” (Groot, 1996).

“Eyed-Eggs”

The eyed-stage is a relatively stable status and is the preferred stage for egg handling without causing harmful effects (for example counting, transport, manipulation in hatcheries etc). Depending on temperature the head and body regions becomes recognizable (Velsen, 1980) and the embryo is clearly visible inside the egg with the attached yolk sac for endogenous feeding.

Hatching

The hatching time depends on the physiological development of the embryo and when the point is reached where the egg membrane cannot maintain the exchange rates between oxygen and metabolic waste, hatching commences. Initiation of hatching occurs by rapid corrosion of the egg capsule and the larval fish quickly ruptures the remaining shell and burst out to become in direct contact with fresh, oxygenated water. After hatching the larvae can absorb oxygen twice as much as during the egg phase as they obtain oxygen through the gills (Groot, 1996).

Larvae

Immediately after hatching the larvae have a spherical yolk sac and a bent body. Within a day the yolk sac becomes elongated and the body straightens (Groot, 1996). The larvae have limited mobility and typically move deeper in the protecting gravels (Bams, 1969). With further development the yolk sac decreases in size as the yolk materials are absorbed for endogenous feeding. When the larva reach its maximum size it is prepared to swim up from the protecting interstitials of the river bed into the free water column (Beer & Anderson, 1997), where the exogenous feeding and the exposure to the biotic and abiotic factors of the free water zone starts (emergence).

<u>Incubation Habitat</u>

Although the incubation period is closely tied to spawning, the habitat requirements of embryos and larvae during incubation are clearly different from those to spawning and have to be considered separately (Bjornn & Reiser, 1991).

Controlling factors and processes

The hydromorphological variability during the incubation period affects the habitat during the incubation period mainly in three ways. Firstly, the spawning redds can be dewatered and fall dry (e.g. Becker & Neitzel, 1985) and secondly disturbance events may lead to scouring and wash the eggs out of the egg pockets, or cause mechanical damage (e.g. Merz et al., 2004). Thirdly, precipitation events may serve to increase the input of inorganic and organic fine sediments leading to an accumulation of fine sediments in the interstices of gravel beds reducing the oxygen supply to the eggs and larvae (e.g. Schuett-Hames et al., 1996).

Another important controlling factor affecting the development of salmonids eggs and larvae is the intragravel temperature that regulates on the one hand the total length of the incubation period but can also have direct effects on survival and development rates of embryos and larvae (Armstrong et al., 2003). Basically, the higher the temperature is, the faster is the rate of development and the shorter the incubation period (Bjornn & Reiser, 1991).

Many authors are in agreement regarding the strong relationship between oxygen availability and embryo survival and have emphasized the importance of oxygen supply to deposited eggs (Chapman, 1988; Ingendahl, 2001; Greig et al., 2007). The fundamental process of oxygen supply to incubating eggs is driven by diffusion through the egg membrane while during the larval stage the oxygen is obtained through the gills. If the oxygen concentration is reduced and embryonic or larval oxygen consumption is higher than oxygen supply the development of eggs and larvae is negatively affected and may result in reduced growth, reduced efficiency in yolk conversion, premature hatching or increased mortality rates (Greig et al., 2007). The literature distinguishes between limiting oxygen factors that lead to restricted embryonic consumption and are sub-lethal and those critical oxygen factors that are lethal (Davis, 1975). The oxygen flux through the interstitials of a riverbed is generally driven by complex interactions between parameters describing sediment characteristics of the river bed and non-sediment related processes such as biogeochemical processes or embryonic respiration (Chapman, 1988; Malcolm et al., 2003).

Habitat describing factors

In terms of flow variability the dewatering of spawning redds might be a critical factor for the development of eggs and larvae in the interstitial, although salmonid embryos might survive dewatering of redds for several weeks (Bjornn & Reiser, 1991). Another role of surface hydraulics (water depth, flow velocity) is its influence on the exchange rates between surface and groundwater and consequently on the biogeochemical processes in the hyporheic zone (Chapman, 1988).

Although substrate entrainment and regular bed alterations by flood events are required to maintain the productivity of spawning habitats, intense and frequent bed disturbances during the incubation period can have detrimental impacts on reproduction by destroying eggs and larvae (LaPointe et al., 2004). As the eggs and larvae are nearly immobile they are extremely vulnerable to any disturbances of the stream bed and may lead to mechanical shocks, destructions or displacement (Schuett-Hames et al., 1996). Typical egg burial depths of brown trout range between 5 cm and 25 cm (Crisp & Carling, 1989) and experimental studies have shown that several disturbance events can wash out up to 90 % at 5 cm burial depth (Crisp, 1996). Further, the downstream drifting eggs and larvae suffer mortality rates up to 50 % due to mechanical shocks, starvation and predation (Crisp & Carling, 1989). Another aspect to consider are the high amounts of fine material that can enter the interstitials of the gravel river bed and reduce the permeability progressively. This clogging process can result in a nearly impermeable layer blocking the infiltration of oxygen-rich surface water affecting the oxygen supply of embryos or larvae.

The intragravel temperature is mainly regulated by the temperature of the surface water, the heat capacity of the sediment-water mixture and the interchanges between groundwater and surface water (Bjornn & Reiser, 1991). Typically surface water responds more rapidly to environmental conditions and shows greater annual and diurnal fluctuations than intragravel temperatures (Caissie & Giberson, 2003). Intragravel temperature depends also on up- and downwelling locations. Close to upwelling zones the temperature is mainly regulated by the groundwater inflow and is characterised by the groundwater temperature while in downwelling zones the fluctuations correspond more to the variations of surface water temperature (Cassie & Giberson, 2003). Given these variations, the total time until hatching for brown trout can vary between 25 – 50 days for water temperatures higher than 10°C and up to 200 days for cold water temperatures at approximately 2°C (Jungwirth & Winkler, 1984). Given to this strong dependency on water temperature the calculation of accumulated thermal units (ATU) is a common method to estimate the timing of transition events between development stages (Eq.A.2.9). The ATU describe the sum of the multiplication of mean daily temperatures exceeding 0°C (T_W) and the corresponding number of days (n_d). For instance, a temperature of 10°C for one day lead to 10 ATU and accumulates after 15 days to 150 ATU.

$$ATU = \sum_{i=1}^{N} T_{Wi} \cdot n_{di} \qquad \text{Eq.A.2.9}$$

Applying Eq.A.2.9, the duration for embryonic development can be estimated in a range between 390 ATU and 480 ATU with a mean duration of 430 ATU. The eggs and larvae respond to different intragravel temperatures in terms of developmental rate, growth, viability and competitiveness (Crisp, 1981, Ojanguren & Braña., 2003). If incubation temperature is low during the embryonic stage the hatched larvae might be longer and lighter compared to egg and larvae at warmer incubation temperatures (Bjornn & Reiser, 1991). The egg stages are generally less tolerant to cold temperatures compared to the larval stages (Groot, 1996).

Regarding the oxygen availability it must be distinguished between factors influencing the oxygen supply to eggs and factors that influence the oxygen consumption of eggs, although both are interconnected (Greig et al., 2007). The oxygen consumption of salmonid egg is directly related to the water temperature in the interstitial as metabolic activities increase with increasing temperature (Crisp, 1981). According to Lindroth (1942) and Rombough (1988) the typical oxygen demand starts out low for newly fertilized embryos and increases moderately up to the eyed stage and then increase substantially to a peak around hatching. The peak is followed by a sharp decrease shortly after hatching before the required oxygen is obtained by the gills. During the larval development the oxygen demand increase absolutely but decrease on a per unit weight basis. Fig.A.2.9 draws qualitatively the critical oxygen levels for gravel-spawning fish during incubation.

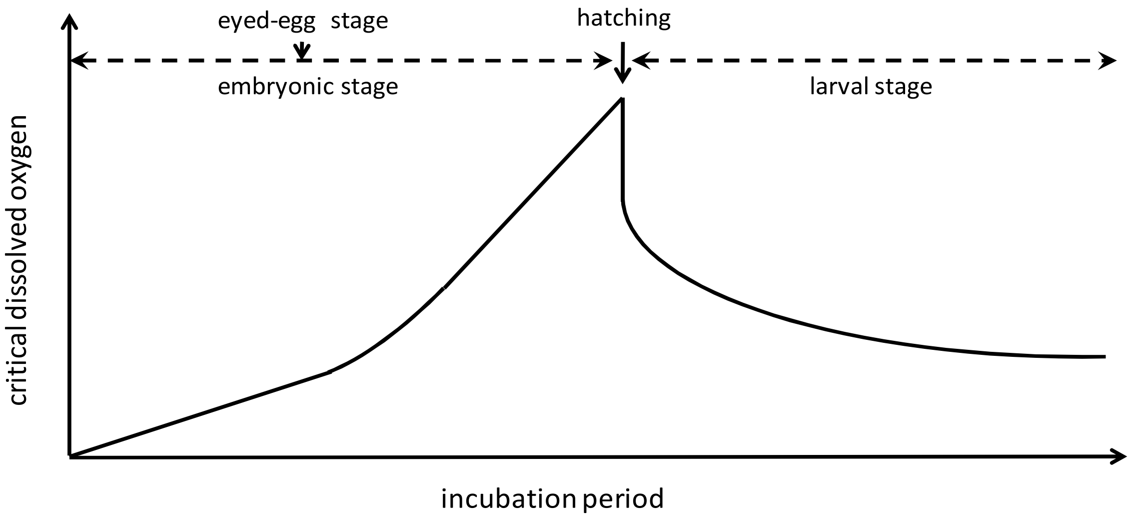


Figure A.2.9: Critical oxygen levels of gravel-spawning fish during incubation period (modified from Rombough, 1988)

Much more complex are the factors influencing the oxygen supply. As the hyporheic zone is the transition area between surface water and groundwater the oxygen contents of both fluxes interchange in the interstitials of the gravel bed defining the oxygen availability for egg development (Greig et al., 2007). Detrimental impacts of groundwater fluxes on intragravel oxygen availability and embryo survival have been reported by Soulsby et al. (2001) and Malcolm et al. (2003) as groundwater usually is characterised by a low oxygen concentration, which is below the required oxygen demands of eggs and larvae. The amount of oxygen-rich surface water infiltrating the hyporheic zone is driven primarily by the surface flow conditions, the vertical hydraulic gradient and sediment characteristics in terms of available pore space and permeability (Schaelchli, 1992). Again, the infiltration and accumulation of organic and inorganic material can block intragravel flow paths and reduce the amount of oxygen-rich infiltrating surface water (Sear et al., 2008). Although the redd is cleaned from fine sediments during redd construction, infiltration processes have the potential to reduce permeability to insufficient values as precipitation or flood events with high amounts of fine sediments are likely to occur during the long incubation period of salmonids (Greig et al., 2005). According to Sear et al. (2008) and Kondolf (2000) permeability reduction is mainly driven by fractions of less than 1mm in particle size. A detailed description of infiltration processes and the influence of accumulation of fine sediments is given in Chapter A.2.3.2. A third component determining oxygen availability is the respiration of oxygen in the hyporheic zone whereby respiration can be of sedimentary, biological or chemical nature (SOD, BOD, COD). The hyporheic respiration is also a function of the residence time of water in the interstitial which results from intragravel flow velocity and length of the flow paths. The longer the residence time the higher the respiration rate (Chevalier et al., 1984).

This brief overview of factors reveals the complexity of determining oxygen availability and its multifaceted interactions with the environment which constitute the difficulty to simulate oxygen availability for embryonic and larval development purposes. Tab.A.2.5 summarizes the main factors that influence habitat quality during the incubation period.

Table A.2.5: Summary of processes and factors influencing the habitat of salmonids during the incubation

Factors	Function
Controlling factors and processes	
hydrologic and morphologic variability	dewatering of redds. scouring and displacement of eggs or larvae, hydrological events defining the delivery of inorganic and organic fine sediments to the river bed
interstitial temperature	duration of incubation period, timing of transition events between development stages, metabolic activity, solubility of oxygen
oxygen availability	developmental rate of embryos and larvae, efficiency of metabolic processes, viability of hatched larvae
Habitat describing factors	
water depth/flow velocity	dewatering of redds, exchange rates between surface and groundwater
sediment entrainment	erosion depth before egg and larvae are washed out of interstitials
particle size distribution	ratio of suspended particle size to sediment-mixture of gravel bed, sediment infiltration, depth of erosion
permeability	accumulation of inorganic and organic fine material, exchange rates between surface water and ground water, transport of oxygenated water to eggs and larvae, transport of metabolic waster products
vertical hydraulic gradient	exchange processes between ground and surface water, intragravel temperature (mixing groundwater and surface water)
oxygen consumption	increasing oxygen consumption during embryonic and larval development, intragravel temperature (metabolic activity)
hyporheic respiration	sediment, biological, chemical oxygen demand (SOD, BOD, COD), influence on oxygen availability
water residence time	the longer the residence time the higher the hyporheic oxygen demand

Emergence Period

Process of emergence

Preparation for emergence starts when the yolk sac is almost absorbed and the young fish, now referred as fry, is fully developed. Brown trout start to emerge before the yolk sac is fully depleted (Sternecker & Geist, 2010) but the digestive tract is already functional. Usually they do not move directly upward. Firstly, they use gravitaxis to guide them through the shortest way through the interstitial to the open water zone, or they orient themselves at an angle towards the current flow over the gravel if the shortest way is not available (Groot, 1996). Principally the readiness for emergence of salmonids fry is induced by rising temperature and occurs primarily at night (Elliott, 1986). Shortly before emergence, fry accumulate just below the gravel surface and emerge when the inhibitory effect of daylight is removed. The strong tendency to nocturnal emergence is mainly explained as antipredator adaption (Armstrong & Nislow, 2006). Premature or prolonged emerging usually result in smaller fry or reduced survival rates as they are weaker and less competitive compared to fry that emerged during the peak time (Jonsson & Jonsson, 2009). The timing of emerging fry occurs within a narrow time window in spring, when sufficient food for the first exogenous feeding is available. With dispersion in the free water zone and defending of established territories (rearing habitats) the reproduction period is completed.

Emergence habitat

Controlling factors and processes

Fry are highly sensitive to hydromorphological variability in terms of floods with gravel movements occurring around the time of emergence as emerging fry are easily drifted downstream or experience physical damage by gravel movements (Tetzlaff et al., 2005). Another important factor regarding successful emergence are the sediment characteristics that have to provide connected pore spaces that are large enough for passing emerging fry (Kondolf, 2000).

Light is a further controlling factor for emergence. Shortly after hatching and until the onset of emergence fry exhibit a strong photonegative (response to light) and geopositive (response to gravity) behaviour, keeping the young fish in the darkness of the interstitial where they are protected from predators (Rubin, 1998). At the beginning of the emergence period they reverse these responses causing them to swim up out of the interstitial (Helfman et al., 2009).

The temperature regime is another major parameter determining the timing of emergence. Most all temporal variations of emergence are due to variations in water temperature (Jonsson & Jonsson, 2009). Low temperatures will result in slow development rates and late emergence leading to smaller and more sensitive fry (Einum & Fleming, 2000).

Habitat describing parameters

For the time around emergence fry are highly vulnerable to surface hydraulics as they are not strong enough to resist high flow velocities and can be drifted downstream (Tetzlaff et al., 2005). Moreover, high flows may put bed material into motion and physically damage the emerging fry. In addition a sufficient water depth must be available.

The sediment characteristics of the riverbed define the available connected pore spaces that allow movements of fry in the interstitials. If the interstitials pathways are too small to permit passage, emergence can be impeded (Bjornn & Reiser, 1991). According to Sear et al., (2008) and Kondolf (2000) not only the silt and clay fraction but also the coarser sand-sized fractions affecting the emergence of fry. However, infiltration of fine sediments during the incubation period may block the interstitial pathways or form an impenetrable clogged layer over the surface of the riverbed (surface colmation, Lisle, 1989). This surface colmation acts as a physical barrier for the emerging fry resulting in entombment (Sternecker et al., 2010). The sediment characteristics for emergence can be approximated by analyses of pore space and particle size distributions.

Interstitial temperatures and light conditions are parameters affecting the timing of emergence. Thus they are important for regulating the duration of the incubation period but do not describe the habitat characteristic. Tab.A.2.6 summarizes the main factors and their functions influencing habitat conditions during the emergence period.

Table A.2.6: Summary of processes and factors influencing the habitat of salmonids during the emergence period

Factors	Function
Controlling factors and processes	
hydrologic and morphologic variability	drifting of emerging fry, physical damage of fry due to gravel movements
light	indicates readiness for emergence (shift in phototactics), predator protection (post-emergence)
interstitial temperature	timing of emergence
fitness	timing of emergence
Habitat describing factors	
water depth/flow velocity	drift of post-emerged fry, available water depth for emerging fry
particle size distribution	amount of infiltrated material, colmation layers
pore space	interstitial pathways to allow movements of emerging fry

Total reproduction

For the entire cycle of reproduction, which is referred here as total reproduction, salmonids need to find suitable spawning gravels, be able to dig a nest, must have sufficient oxygen availability during the incubation period within preferred temperature limits and interstitial pathways have to available to emerge from the gravel bed into the free water zone. In assessing the suitability or quality of river reaches for reproduction purposes of salmonids the different environmental requirements in each life stage have to be considered (Kondolf, 2000). Moreover, the success of total reproduction can be significantly reduced or lead to 100 % mortality by single impairments during each development phase of the reproduction cycle. Hence, the suitability or survival of each development stage (spawning, embryonic, larval and emergence phase) have to be linked to get an idea about the total reproduction rate. But the number of processes and factors influencing reproduction success is very high and they interact in a complex manner between abiotic processes and biotic responses (Crisp, 1996). In addition these complex interactions are characterized by an enormous spatial and temporal variability which constitutes a challenge for monitoring reproduction parameters properly. Therefore the habitat quality and the requirements during each development stage cannot be defined precisely or be fully quantitatively described (Bjornn & Reiser, 1991).

Although many investigations were conducted to estimate the egg-to-fry-survival (ETF-survival) it is difficult to draw any firm generalizations given to the high variability of published mortality rates during the reproduction process. According to Dumas and Marty (2006) the egg to fry survival for wild salmonids can range widely from 0 % to more than 90 % in the same river, whereby the mean values of ETF-survival rates vary between 2 % and 35 % in natural rivers. Tab.A.2.7 shows a summary of published mean ETF-survival rates obtained in natural and laboratory studies.

Table A.2.7: Survival rates for salmonids during the reproduction period

	eyed-egg	hatching	emergence	species
Kelly et al. (2007)	89 %	43 %	22 %	Brown trout
Ingendahl (1999)	73 %	38 %	17 %	Atlantic salmon
MacKenzi & Moring (1988)	89 %	74 %	2 %	Atlantic salmon
Pauwels & Haines (1994)	65 %	31 %	7 %	Atlantic salmon
Flanagan (2003)	93 %	82 %	63%	Atlantic salmon

Pure egg survival for salmonids is generally quite high as the egg pockets are covered with gravel and the oxygen supply is ensured given to the recent cleaning during redd digging. Moreover, the oxygen requirements of eggs before hatching are low compared to the proceeding development. With ongoing development the influence of the complex environmental variables is increasing with increasing demands on oxygen availability resulting in higher mortality rates around the time of hatching. According to Sedgwick (1982) it is generally accepted that the hatching stage is more vulnerable compared to the egg stage. In terms of fry emergence, the high variability of survival rates in Tab.A.2.7 further reflects the growing influence of environmental conditions. The low survival rates for the emergence stage in Tab.A.2.7 are in coincidence with investigation of Dumas & Marty (2006) who found the highest mortality between hatching and emergence.

A.2.3 The hyporheic interstitial

Next to morphology and ecology a third research area – the hyporheic interstitial - is influencing the reproduction of gravel-spawning fish and has gained growing attention in recent decades for assessing habitat quality (Tonina & Buffington, 2009). For a proper habitat description during the reproduction period the dynamic processes in the interstitial in terms of morphology but also in terms of biogeochemistry have to be taken into account to estimate the quality of reproduction habitats.

A.2.3.1 Definition of the hyporheic zone

The ecological relevance of the hyporheic interstitial as the transition zone between groundwater and surface water was firstly recognized by Orghidan (1959) who termed this zone as 'hyporheic biotope'. Schwoerberl (1961) firstly combined the aquatic community environmental conditions to consider the hyporheic interstitial as an integral part of fluvial ecosystems (Bretschko & Klemens, 1986; Brunke & Gosner, 1997). Orghidan defined the hyporheic zone as 'hyporheal' and the living organisms their 'hyporheos'. The term hyporheic interstitial originates from a combination of Greek and Latin expressions: the Greek words 'hypo' means 'under' and 'rhe' means 'flow', while the Latin term 'interstitium' means 'interstices'. Together this can be translated as the 'flow in the interstitial subsurface' (Tonina & Buffington, 2009). Several definitions for the hyporheic interstitial can be found in literature. For example White (1993) proposed a conceptual definition for the hyporheic zone as being the saturated interstices beneath the river bed that contain some proportion of surface- and groundwater. Another more functional definition emphasized the dynamic ecotone model theory (Boulton et al., 1998). This definition considers the difficulties to define boundaries of the hyporheic zone because they are strongly variable over time and space, the shared environmental features of both compartments in terms of gradients over different scales, physical-chemical processes and the importance of the sediment characteristics. Hence, the habitat patches for reproduction of fish and other hyporheic organisms are mainly controlled by the dynamics and heterogeneity of these exchange processes in the hyporheic interstitial.

In terms of hydromorphology, the hyporheic interstitial is characterized by alternating infiltration of surface water into the fluvial sediments of the river bed (downwelling/influent flow conditions) and exfiltration of groundwater into the river (upwelling/effluent flow conditions). This up- and downwelling processes depend on the river morphology, local sediment characteristics and flow rate (e.g. Borchardt & Pusch, 2009). The exchange occurs on a wide range of scales (Packman & Bencala, 2000) both vertically into the hyporheic zone and laterally into the parafluvial zone (Boulton et al., 2007).

Although there is profound knowledge available about processes occurring within surface water and groundwater itself, less is known about the processes occurring at the interface of a river and an aquifer on different interstitial scales (Killeen, 2009). Therefore the following sections provide information about the hyporheic exchange processes on different interstitial scales as well as the most relevant morphologic and ecological processes.

A.2.3.2 Hydrologic exchange on different interstitial scales

Hyporheic exchange on a macro-scale

The macro-scale includes exchange processes on a catchment and segment scale. According to the hyporheic corridor concept (Stanford & Ward, 1993), the major controls on hyporheic biodiversity and exchange processes on the catchment scale are the alluvial flow paths and residence times whereby the subsurface continuum also encompasses landscape features that are connected to the river system such as riparian zones, paleochannels and floodplain aquifers (Boulton et al., 1998). Macro-scale exchange processes between the hyporheic interstitial and surface can be identified as a series of points (hotspots) that are interspersed with unconstrained alluvial reaches (fractal scaling). According to Zimmermann & LaPointe (2005), the hyporheic flow on macro-scale is governed by differences in pressure head (produced by elevation and pressure potentials) between the water level in the river and the groundwater table. The subsurface flow on the macro-scale is usually characterised by deep penetration and a long residence time within the subsurface environment (Killeen, 2009). In addition different hyporheic flow patterns can be observed in different catchment areas and thus the exchange pattern is also related to the geologic and drainage control of a catchment (Morrice et al., 1997).

Hyporheic exchange on a meso-scale

Exchange processes in the hyporheic zone on the meso-scale are usually associated by the interactions between river hydrodynamics, geomorphologic and topographic features such as slope, riffle-pool-sequences, gravel bars and gravel islands that alter the surface and subsurface flow paths depending on permeability (Revelli et al., 2008). The principal driver for exchange processes is the creation of pressure differentials above the bed. Generally two types of pressure gradients are distinguished on the meso-scale (Vollmer, 2005): The vertical hydrostatic head gradient that induces hyporheic exchange due to discontinuities in the slope such as step-pool- or riffle-pool sequences as well as the horizontal hydrostatic head gradient generated by planform morphology from meanders and gravel bars. The resulting horizontal (e.g. meandering) and vertical (e.g. riffle-pool-sequences) convexities and concavities of the river shape control the interactions between subsurface and surface flow and are mainly uncoupled from the macro-scale exchange processes between the groundwater aquifer and surface water (Brunke & Gonser, 1997). The length of the flow paths in the subsurface area and the corresponding residence time depend typically on the lengths of the geomorphic features and the permeability of the subsurface sediment structure.

Hyporheic exchange on a micro-scale

On the micro-scale interstitial flow patterns mainly depend on the sediment characteristics, including size, shape and composition of particles, the available pore sizes and the different hydraulic gradients in terms of strength and direction (Boulton et al., 1998). Key processes at the micro-scale include those that have the potential to alter the size and amount of interstitial space, such as colmation with infiltrating organic and inorganic material. On this scale hydrodynamic pressure gradients are generated, that induce a hydrological exchange which might overlap with hydrostatic pressure head on larger scales. According to Kaeser et al., (2009) the hydrodynamic pressure heads on micro-scale are mainly driven by two processes: The first one is due to turbulent diffusion and is caused by the transfer of momentum between stream and pore-water flow. Basically, this diffusional mass is induced by the hydrodynamics of the surface flow and its pressure variations above the sediment surface (Higashino & Stefan, 2008). The second process is the hydrodynamically induced advection, also known as pumping (Zimmermann & LaPointe, 2005) caused by the flow over micro-scaled bed forms or obstacles. The flow is accelerated over the bed form and results in a high pressure zone upstream of the bed form and induces flow in and out of the river bed (Worman et al., 2002). Given these highly dynamic fluctuations, zones of rapid, slow and no flow (dead zones) are created all over the river bed resulting in a variable structure of the hyporheic exchange processes. Even in rivers with seemingly well-oxygenated hyporheic zones, dead zones can co-exist leading to anaerobic conditions (Boulton, et al. 1998) that can have detrimental impacts on hyporheic organisms. The Figure A.2.10 from Stonedahl et al. (2010) illustrates schematically the hyporheic flow on multiple scales.

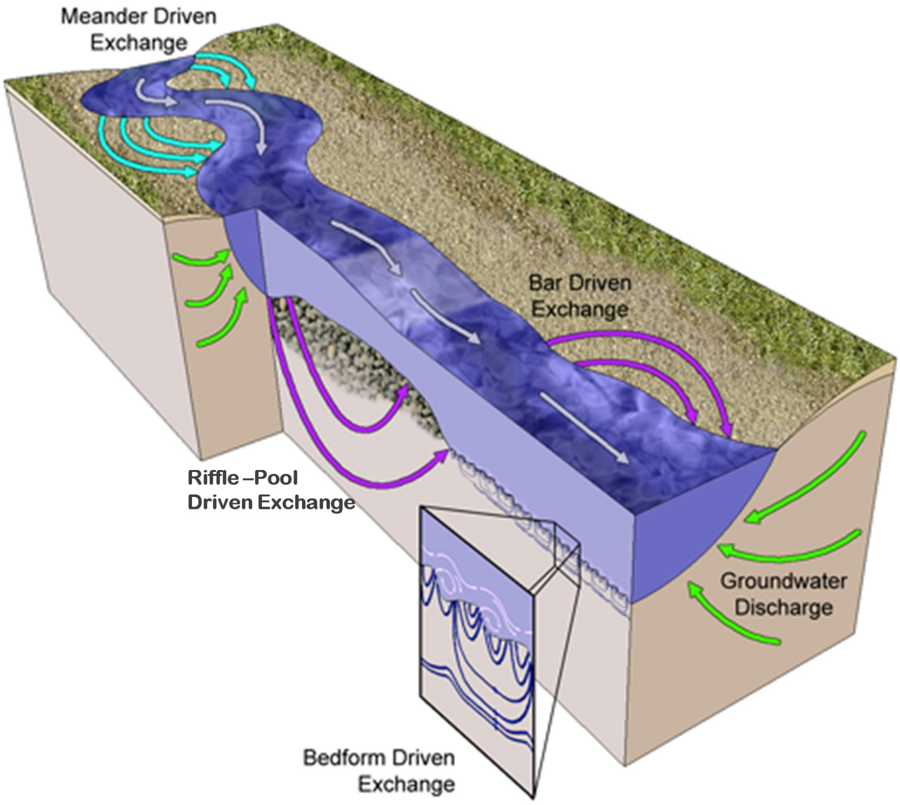


Figure A.2.10: Exchange processes in the hyporheic zone over multiple scales (modified from Stonedahl et al. 2010).

It is emphasized that hydrological exchange and mixing processes in the hyporheic zone have a highly dynamic character and may change widely over all spatial and temporal scales (Brunke & Gosner, 1997). The processes inducing hyporheic exchange on different scales are not mutually exclusive and may overlap each other (Saenger & Zanke, 2009).

A.2.3.3 The interstitial zone from a morphological point of view

The influence of morphologic characteristics on the hyporheic zone is regarded as the major driver of hyporheic flow and exchange processes (Cardenas, 2008). The influence of hydro-morphological processes covers the entire range of the spatial scales, including flood-related disturbances shaping the river morphology on a macro-scale, generation of geomorphic features on a meso-scale, and sediment infiltration on a micro-scale. Each of these processes is significantly related to the hyporheic zone and can alter the direction of subsurface flow paths and residence times due to changing pressure gradients and changing sediment characteristics. As the morphology of river dynamically responds to geomorphic processes (Chapter A.2.1.2) the effects of morphodynamic processes lead to both a spatial and temporal variability of hyporheic flow (Wondzell & Swanson, 1999).

Geomorphic features

As previously mentioned the influence of topographic and geomorphic features on hyporheic exchange processes can be subdivided into longitudinal morphologic and planform morphological characteristics.

The significance of longitudinal morphologic characteristics for hydrologic exchange has been mainly demonstrated for pool-riffle-sequences which start at the end of the upstream pool where water downwells into the hyporheic interstitial and displaces the interstitial water. The infiltrated water travels in the subsurface until the end of the riffle and upwells at the beginning of the downstream pool (Fig.A.2.10). The hyporheic flow across riffles is driven by the drop of the water surface from pool to pool (vertical hydrostatic gradient) that remains relatively constant over a wide range of different flows, except major flood flows (Zimmermann & Lapointe., 2005). For larger changes in slope, (step-pool-sequences) higher pressure heads are induced.

Planform morphologic characteristics such as meandering rivers or gravel bars lead to horizontal hydraulic head gradient variations. If a bar protrudes into the river channel the hydrostatic head becomes higher in the upstream portion and lower in the downstream portion resulting in a pressure gradient across the bar that induces hyporheic exchange (Fig.A.2.10). In meandering rivers with sharp river bends, inclinations of the water levels occur that induce sizeable pressure gradients along relatively short pathways between opposite banks of the same meander. Consequently a sinuosity-driven hyporheic exchange is established that controls the intrameander hyporheic environment (Revelli et al., 2008).

Bed disturbances during hydrological events

High flow events and related bed disturbances essentially define the sediment characteristics which include the size of the interstitial pores and permeability which are important parameters for hyporheic exchange. Furthermore major floods might have the capacity to restructure the river shape by scouring new pools and depositing sediments as new riffles and consequently alter the number and location of riffle-pool-units affecting the extension of the hyporheic zone. Consequently up- or downwelling zones become shifted (Wondzell & Swandson, 1999).

Typically in natural gravel river beds that exhibit an armoured surface layer, a permeability that is larger than the permeability of the subsurface layer is observed, as the fine sediments are removed from the armoured layer. During the increasing flow of hydrological events, Allen & Frostick (1999) observed that with beginning entrainment of the bed structuring gravels, the pore spaces dilate and fine sediment can penetrate deeper into the gravel framework and thus increase the consolidation and lowers the permeability in subsurface zones. With further entrainment and breaking of the armoured layer the gravel-framework and vertical stratification of sediment layers becomes completely disorganized and particles are fully redistributed. (Reid & Laronne, 1995) This results in a considerable increase of permeability given to the newly low consolidated sediment structure (Schaelchli, 1993).

Infiltration and accumulation of fine sediments into the river bed

The investigations of fine infiltration into gravel river beds have a long history, especially with its influence on spawning or reproduction success of salmonids (Sear et al., 2008). In contrast to colmation (Chapter 2.1.4) which is an integrated descriptor of hyporheic conditions, the sediment infiltration purely consider the sedimentological occlusion of pores in the river bed gravel-framework. The rate of infiltrating material and its spatial and temporal heterogeneity is related to the supply of sediments to the gravel bed, the transport type in terms of suspended and bed load (Carling, 1984), the local hydraulics (Einstein, 1968), the dimensions of the interstices between the sediment framework (Frostick et al., 1984), scour and fill sequences during hydrological events (Lisle, 1989; Schaelchli, 1993) and river morphology (Diplas & Parker, 1992).

According to Sear et al (2008) the dominant processes controlling the character and distribution of fine matrices in gravel frameworks can be considered in two groups. The first group consists of the infiltration processes acting from the water column delivering fine sediments to the pores in the upper surface of the sediment layers and the second group consists of the processes acting within the sediment to redistribute the delivered material in the pore spaces.

Infiltration of fine sediments from the water column

The infiltration of fine sediments from the water column neglect the transport of infiltrated material through the interstices by interstitial flow. The movements of fine sediment from the water column to the river bed (Chapter A.2.1.3) occur through gravity-driven settling processes or through advection towards the river bed by fluid turbulences. Cuthberton (2001) found that gravity-driven settling is the dominating process for particles > 0.35 mm while turbulence-driven settling influences particles < 0.35 mm. These two processes are the key processes in delivering fine sediments to the surface of the river bed. The infiltration into the uppermost sediment layer begins again either by gravity-driven or by flow movement, but with additional control of the characteristics of the particles forming the gravel framework.

Early investigations (Einstein, 1968) observed settling of fine particles in the bottom of the gravel framework. This was later disproved by several following experimental investigations (e.g. Schaelchli, 1993) that showed infiltration up to a finite depth within a few diameters of the coarsest grains in the gravel framework. This indicates that other factors than gravity control the movement and distribution into subsurface pores, for instant. the ratio between the size and shape of the infiltrating material and the size and shape of the available pores within the gravel framework as well as bed disturbances and particle movements in the gravel framework by interstitial flow (Sear et al., 2008).

Schaelchli (1993) examined infiltration and clogging processes based on the cake filter theory and developed a semi-empirical approach to calculate the water volume penetrating the hyporheic interstitial. He distinguishes three phases of sediment infiltration from the water column (Fig.A.2.11) and consider a vertical stratification of sediment layers. This stratification includes a course widely-pored armoured surface layer and a following subsurface layer that acts as a filter layer. Furthermore he observed that only the finer fractions (< 1 mm) lead to significant reductions in permeability while infiltration and deposition of sandy material has a comparably low influence on permeability.

Phase 1: The dominating process during the first phase is the infiltration and deposition of coarser particles (approximately d=2 mm) in macro-pores reducing the interstitial pathways by occlusion or bridging. In this phase smaller particles can still penetrate deeper into the gravel framework and the effect on permeability during this phase is low and can usually be neglected.

Phase 2: Deposition of the mean particles (approximately d=1 mm) in the remaining pores of the subsurface layer is the dominant process of the second phase. The permeability is reduced drastically given to the decrease of the pore diameters. Infiltrating fine material can hardly penetrate deeper into the interstices and are trapped on the earlier infiltrated larger particles.

Phase 3: The dominating process during the last phase is the deposition of fine material (d< 1 mm) on the interface between surface and subsurface layer forming a nearly impermeable sealed layer with progressing but decelerating reductions of permeability.

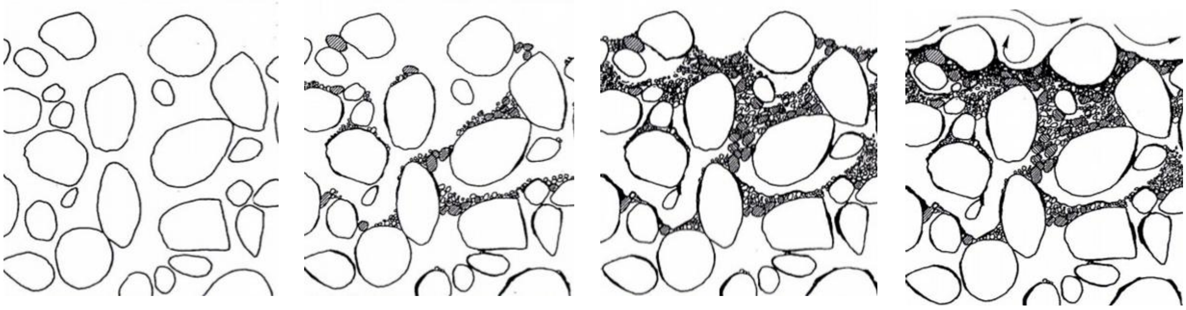


Figure A.2.11: Infiltration and accumulation of fine sediments in the gravel framework of a river bed divided in three phases with different dominating processes (modified from Schaelchli, 1993)

These three phases describe the progressive clogging processes until a nearly impermeable colmation layer (Chapter A.2.1.4) is formed. At the beginning of the colmation development coarser particles are more important compared to fine particles but with increasing colmation development the dominating process is shifted towards the fine materials. Regarding the vertical development the clogging process starts within a few diameters of the largest grain size of the gravel-framework and travels towards the armoured layer and ends on the interface between the surface armour layer and the subsurface filter layer (Schaelchli, 2002). However the actual penetration depth depends on further transport mechanisms such as diffusion, trapping and hydrodynamics, as well as on the electrostatic forces on the particles such as chemical and biological reactions (Saueregger, 2009). The infiltration rate of fines sediments changes over time even if all other involved parameters remain constant as the reduction in pore space due to infiltrating sediments increase the probability for subsequent incoming fine sediments to become lodged (Cui et al., 2008). This process results in a decreased fine sediment fraction with increasing sediment depth and proceeds until the deposition and resuspension of particles are in equilibrium and no more fines can intrude into the subsurface layer. According to Schaelchli (1995) this continuously increasing infiltration resistance depends on the particle size composition of the gravel framework, the viscosity of the water, the permeability, and the shear stress.

If the composition of the gravel framework is characterised by large pores the infiltration resistance is small, as fine particles can easily intrude the interstices and firstly have to fill the large pores. Similarly the lower the viscosity and the higher the hydraulic gradient the higher the infiltration velocity resulting in small infiltration resistances. Shear stresses exhibit the opposite relationship, as with increasing shear stress the infiltration resistance is also increased as the infiltration processes is accelerated due to higher turbulent fluctuations of the shear stress that lead to a vibrating effect on the gravel framework and dilates the pores allowing deeper and denser deposition of fine particles (Sear et al., 2008).

<u>Bed filtration in the interstitial gravel-framework</u>

Filtration and clogging of pores is also a result of transport processes in the riverbed (Bunte & Abt, 2001). Surface water or groundwater infiltrating the interstitials can transport the fine sediments laterally and vertically either by suspension or direct transport. The strength of the hyporheic flow depends mainly on the hydrostatic and hydrodynamic pressure gradients as they are described in the previous sections. Carling (1984) and Seydell et al. (2009) compared the sediment infiltration process with permeable and impermeable side walls of sediment traps and found that the trap efficiency is considerably reduced for impermeable sediment traps indicating the lateral transport of fines in the sediment interstitials. The dynamics of hyporheic flow during flood events have an effect on bed filtration processes. The exchange patterns during a flood show that during the rising limb a negative hydraulic gradient occurs indicating the infiltration of surface water, while during the recession limb positive values indicating exfiltration of ground water into the hyporheic zone occur (Malcolm et al., 2006). These changing flow directions as well as the entrainment and dilation processes significantly affect interstitial transport processes of fine sediments and cannot be neglected when assessing infiltration dynamics (Sear et al., 2008).

As described above these sedimentary and colmation processes effect the hydrological exchange processes leading to very heterogeneous patches of different environmental conditions for hyporheic organisms. Thus, it can be stated that the dynamics of interstitial sedimentary processes play a crucial role in determining the interstitial habitat quality and cannot be ignored in the assessment of reproduction success of gravel-spawning fish.

A.2.3.4 The interstitial zone from an ecological point of view

Next to the hydromorphological features, the hyporheic interstitial is also a functional zone for biological activities in the form of biofilms and geochemical cycling of nutrients and contaminants influencing the physiochemical characteristics, especially the dissolved oxygen content of the hyporheic habitats (Killeen, 2009). Therefore the content of this chapter focuses on the hyporheic aquatic community, the ongoing biological and geochemical processes and explicitly deals with the influence of hyporheic processes on the reproduction of salmonids.

The hyporheic aquatic community - hyporheos

Gibert et al. (1994) define three major groups of macro-organisms living in the hyporheic interstitial: occasional hyporheos, amphibites, and permanent hyporheos. The group of occasional hyporheos may reside in the hyporheic zone temporarily whereas during their later life-stages they predominately reside in other habitat zones (e.g. open water zone). To this group belong diverse macroinvertebrates (e.g. mayflies) but also the gravel-spawning fish species as the embryonic and larval development during reproduction is progressed in the hyporheic zone. The group of amphibites is mainly comprised of aquatic insects that complete their larval development in the hyporheic interstitial (e.g. stoneflies). The last group – permanent hyporheos – completes their entire life-cycle in the hyporheic zone such as crustaceans, worms and rotifers. Next to this classification of macro-organisms the hyporheic zone provides habitats for many micro-organisms and it has been shown that the role of microbial activities as transformers of dissolved and particulate nutrients strongly influence the physical-chemical environment in the hyporheic zone.

Biogeochemical processes and hyporheic respiration

In general the interactions between sedimentological, chemical, and biological parameters are summarized as biogeochemical processes. Given the long residence time of subsurface flow, microbially-mediated biogeochemical processes are promoted that are vital to the whole fluvial ecosystem (Harvey & Wagner, 2000). In the hyporheic zone this comprises the mineral sediment characteristics, interstitial flow, organic and biogenic material, biological communities, as well as nutrients and contaminants. The temporally and spatially variable exchange processes results in gradients of these variables (Huettel et al., 2003) and thus control the mixing, transport and pattern of dissolved oxygen, nutrients, contaminants, redox conditions and thus the physiochemical habitat characteristic (Killeen, 2009). Because aerobic decomposition is more rapid and energetically favourable than anaerobic ones, downwelling zones are characterized by higher rates of microbial activity than upwelling zones (Franken et al., 2001). Among the most important biogeochemical processes are the respiration of dissolved oxygen and the mineralization of nutrients.

Dissolved oxygen (DO) and organic carbon

Since the only supply of DO to the hyporheic zone depends on the infiltrating surface water the hyporheic zone has a limited oxygen budget and given to its heterotrophic nature anaerobic patches along the interstitial flow paths occur, especially in areas where aerobic metabolic activity is high and permeability low (Greenwald, 2008). The rate of metabolic activity depends largely on the supply of dissolved or particulate organic carbon (DOC, POC) which are the principal drivers for oxygen respiration in the hyporheic zone. The amount of organic matter is taken up by the microbes and gets subsequently mineralized and are returned to the stream in inorganic form. The development of dissolved oxygen gradients in the hyporheic zone is one of the most important biogeochemical processes as the development of anaerobic zone support other microbially reactions that influence the abundance and specification of important nutrients in the hyporheic zone. Moreover, the respiration of oxygen due to oxidation of organic matter is in direct competition with oxygen demand on eggs and larvae of salmonids during the incubation period (Sear et al., 2008).

Transformation of nutrients

The nutrient (nitrogen, phosphorus) transformations depend on the concentrations of DO and organic matter as well as on the abundance of various nutrient species (Dent et al., 2000). Depending on the redox potential in the hyporheic zone a wide range of different biogeochemical reaction are facilitated. In terms of nitrogen, the most important biogeochemical processes in the hyporheic zone are nitrification, denitrification, and ammonification. Nitrification is an aerobic process where microbial organisms oxidize ammonia to nitrate while denitrification is a metabolic process and includes the reduction of nitrate to nitrogen gases and thus removes nitrogen from a system. The ammonification transfers organic nitrogen into ammonium. The dynamics of phosphorus are driven by both biotic and abiotic processes. Abiotic processes include the sorption of phosphorus on inorganic particles depending on the pH and redox potentials. If conditions are reduced, phosphorus can be released from the complexes and become soluble (Hendricks & White, 2000). Biotic processes comprise the mineralization of organic matter and the subsequent release of inorganic phosphorus.

Influence of biofilms on biogeochemical processes

The hyporheic zone which serves as an interface between oxidized surface water and reduced groundwater is an ideal environment for micro-organisms which derive their energy from the oxidation of inorganic materials (Storey et al., 1999). Those micro-organisms are most active in biofilms comprised by fungi, bacteria and protozoa and are regarded as an important storage site for organic matter. The large internal surface area of microbial biofilms and the complex system of pore spaces provide sorption sites that enable the retention of organic material. According to Fischer et al. (1996) heterotrophic bacteria are the main component of biofilms and contribute more than 90 % of the total metabolism processes. Biofilms vary in nature from large visible ones to microscopic ones. Generally the amounts of organic matter (DOC and POC) are the major energy source which is not readily available for all consumers but has to be processed by the microbial community. Therefore the biogeochemical transformations require oxygen for the remineralisation processes of organic matter and release bound nutrients for surface productivity. The total oxygen respiration in the hyporheic zone reduces the availability of oxygen for reproduction purposes of salmonids and has to be considered as an important parameter for describing the reproduction habitat quality.

Hyporheic processes and the reproduction of salmonids

The term hyporheic originates mainly from biological investigation dealing with the microbial processes and invertebrates. It has been rarely used in fisheries research, although the influence of the exchange processes on embryo survival was early recognized (e.g. Vaux, 1968). Moreover most fisheries research was focused on sedimentary processes neglecting the wider understanding of the hyporheic zone and its processes (Malcolm et al., 2008). This section provides a brief overview of hyporheic processes and their relation to the reproduction of gravel-spawning fish.

Hyporheic flow through spawning redds

Until now the hyporheic flow paths have been discussed without taking into account the special topographical changes that occur during redd construction of salmonids. Tonina (2005) and Sear et al. (2008) described the influence of redd morphology on both surface and subsurface flow paths and interstitial velocities [cm/h] as it is visualized in Figure A.2.12.

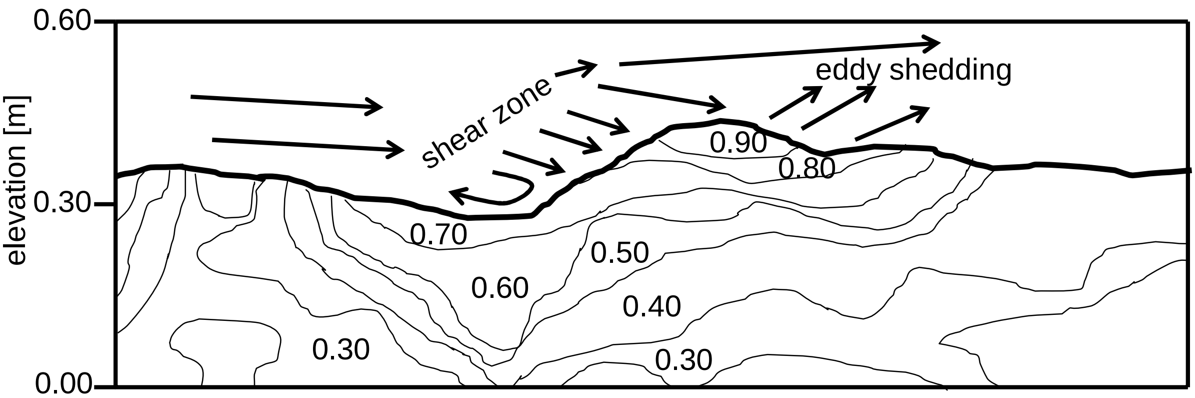


Figure A.2.12: Flow pattern over a salmonids redd with hyporheic flow paths and interstitial velocities (modified after Sear, et al. 2008)

Basically, the hydrodynamic pattern is influenced by the typical redd morphology including the pit upstream and the tailspill downstream. These features are typically below and above the original river bed (Tonina, 2005). The pressure gradient between the upstream and downstream parts of the tailspill forces surface water to infiltrate into the spawning redd and results in increased interstitial velocities within the egg zone and tail. This infiltration can exceed the surrounding interstitial velocities by a factor between 4 to 6 (Zimmermann & LaPointe, 2005). Given this downwelling zone, the supply with dissolved oxygen as well as the removal of metabolic waste products is supported. Further downstream, weak flow separation occurs at the upstream edge of the pit creating upwelling eddies in the low pressure zone downstream of the tailspill. Tonina (2005) found in his investigations that the larger scaled hyporheic flow induced by the geomorphic feature (pool-riffle-unit) is not superimposing the local hyporheic flow characteristics.

Thus the interstitial habitat quality which is defined by the hyporheic flow induced by a geomorphic feature can be significantly improved by redd construction as oxygen-rich surface water is driven through the egg pocket resulting in higher interstitial velocities, a higher supply of oxygen and a sufficient removal of metabolic waste products (Geist, 2000). However given the long incubation period the typical redd morphology can flatten out due to sediment-transport processes in the river or the interstices become filled with accumulating fine sediments reducing the favourable exchange pattern and its benefits (Killeen, 2009).

Impact of sediment infiltration processes

Impacts of sediment infiltration processes on the incubation period of salmonids have been studied for several decades. According to Malcolm et al. (2008) mainly three processes affect the survival of the embryo and larvae in the egg pocket. The first is the reduction of pore space due to accumulation of fine sediments that decrease the interstitial flow velocity and therefore increase the residence time, which consequently reduces the DO delivery to the eggs and larvae. This process may even be supported by freshly constructed redds as the moved particles are loosely packed and contain large pores that allow easier infiltration in comparison to the surrounding gravels (Lisle, 1989). Secondly, the infiltrating sediments have an oxygen demand on their own that additionally reduce the DO delivery to the sediments. This becomes even more drastic when large amounts of DOC/POC enter the spawning gravels which increase the oxygen respiration. Furthermore, the microbial processing of organic matter may lead to the creation of biofilms (Stonedahl et al., 2010) that additionally reduce the available pore sizes for interstitial flow paths and increase the biogeochemical processes supporting the anaerobic conditions in the hyporheic zone (Boulton et al., 1998). A third process affecting the incubation period is the physical capping of redds by a surface sealing layer. Even a thin colmation layer can completely inhibit hydrological and nutrient exchange processes producing anaerobic zones in the hyporheic interstitial (Tonina & Buffington, 2009). Moreover the sealed surface layer inhibits the emergence of fry into the open water zone and traps them in the interstitials.

Finally, it can be stated that more or less all hyporheic processes may have an impact on the supply of oxygen to the embryos or the larvae of salmonids. This supports the importance of hyporheic processes to be considered in determining the habitat quality of gravel-spawning fish during the reproduction period.

A.3 Numerical modelling

Models can be defined as a replica of a multifaceted natural reality with the ability of qualitative or quantitative prediction (Darby & van de Wiel, 2005). This means, for example that natural processes are conceptualized to a form which corresponds to available resources (e.g. knowledge level, computer technology). There is a wide range of modelling types ranging from conceptual models over analytical models to statistical models and numerical models. The main advantage of using numerical models is their capability to deal with spatial and temporal dimensions. The principle functionality of a numerical model is to describe a physical process in a mathematical form. Subsequently a numerical algorithm is required to solve or approximate a predefined equation on a spatially discretized grid for various time steps. Due to advancements in computer technology numerical models are widely applied for solving engineering issues today and (more recently) for ecological aspects by incorporating multiple dimensions and multiple spatial/temporal scales.

A.3.1 Numerical modelling of morphodynamics

Computational methods of morphodynamics are able to solve sets of non-linear differential equations describing hydrodynamics, sediment-transport and morphological changes of river beds. In order to close the required mathematical systems many assumption and empirical formulas have to be applied. Sediment researches worldwide developed numerous methods and equations which led to a wide range of different model types for specific aspects (Wu, 2007). The next chapter provides an overview of computational concepts in modelling sediment-transport.

A.3.1.1 Classification of computational concepts for sediment transport

On the basis of Wu (2007) and Papanicolaou et al., (2008) morphodynamic models can be classified according to their spatial and temporal continua (dimensionality), their implementation of sediment-transport modes, their numerical methods and their coupling to hydrodynamic modelling components.

Dimensionality

Generally both hydro- and morphodynamics are 3D-phenomena. However, depending on application purposes a simplification to 2D- and 1D-sediment transport models can be established by section-, depth- or width-averaging to achieve feasible solutions in engineering practices.

<u>One-dimensional models:</u>

1D-models are formulated along the longitudinal river course using cross-section averaged variables of flow and sediment transport. 1D-models solve the differential equations of mass conservation and flow momentum (St. Venant equations) along with sediment mass continuity (Exner-equation) using the finite difference method. Most 1D-models are capable to compute bed level variations, bed-, suspended- or total load and can deal with non-uniform grain size distributions. Furthermore, they have additional features developed for specific application purposes. Given to the easy use and low requirements on computer technology 1D-models are still a valuable tool, especially for large-scale and long-term modelling purposes (Wu, 2007).

Two-dimensional models:

2D-models are averaged either vertically or horizontally. As river geometries vary significantly over the width, depth-averaged models are preferred in most applications. 2D-models solve the depth-averaged Navier-Stokes equation and the sediment continuity on a computational grid providing horizontal information about hydrodynamic and morphodynamic processes. There is a wide range of 2D-models which are developed for more or less all types of sediment-transport ranging from reservoir sedimentation, particle sorting, river rehabilitation measures and bed evolution to lake and coastal applications.

Three-dimensional models:

3D-models have gained increasing attention within the latest developments in computer technology. Applications of 3D-models used to be restricted to local fields with strong 3D-features that could not be solved by 2D-modelling (scouring at piers, groyne fields). Today 3D-models are also applicable for simulating bed evolution in natural rivers over a considerable river length and hence, broadened the application area of 3D-models. Similarly to 2D-models they solve the Navier-Stokes equations and sediment mass balance on a computational grid. 3D-models can be further subdivided in hydrostatic and non-hydrostatic models. The latter does not allow predicting 3D-flow in regions with high adverse pressure gradients but have shown to represent secondary flows in complex domains adequately (Ruether & Olsen, 2005).

Sediment-transport modes

Bed-, suspended-, total load:

As sediment transport can be subdivided in suspended and bed load, models are distinguished according to their ability to deal with single or coupled transport modes. Earlier models often considered bed or suspended load or the sum of both as total load. Whereas today most morphodynamic models are capable to calculate suspended and bed load separately by using different transport formula for each transport type.

Number of particle sizes:

Generally speaking, single particle transport models are called uniform while multiple-sized models are called non-uniform models. Uniform models use a single particle size which represents a certain sediment mixture while non-uniform models divide a sediment mixture in several fractions and calculate the transport for each fraction. The occurrence of interactions between fine and coarse particles in natural rivers cannot be taken into account by uniform models. Furthermore Fischer-Antze et al., (2009) and Hung et al., (2009) found non-uniform models yield better agreement with field data due to the fact that sediment of natural rivers are commonly non-uniform. Hence, the non-uniform approach suits better to simulate sediment characteristics correctly.

Sediment-transport state:

The transport states either in form of equilibrium or non-equilibrium represents another classification of sediment transport models. The equilibrium approach employs an empirical relation for the transport rate that corresponds to the sediment transport capacity of the flow. This assumption might be appropriate considering uniform flow and shallow water depths, however, in alluvial rivers the sediment load is typically unable to instantaneously adapt to the quick spatial and temporal variation of flow and the considerable time lags between flow and sediment transport might lead to unrealistic morphological predictions (Bui & Rutschmann, 2010). Non-equilibrium approaches renounce this assumption and adopt transport equation by introducing an adaption length to determine the actual bed and suspend load rates (Wu, 2007).

Sediment layers:

Sediment transport models with bed evolution algorithms are also classified according to their number of sediment layers. A model usually consists of at least two layers: an active layer or bed load layer and an inactive layer that indefinitely extends downwards. Many models though incorporate one or more mixing layers in between to account for vertical particle sorting processes. For instance, Ferreira & Cardoso (2000) consider the bed material as a stratified continuum where the active surface layer acts as a filter for the following mixing layer.

Numerical methods

The most spatial numerical schemes in flow and sediment transport models are finite difference, finite volume or finite element methods. Each of these numerical methods have its pros and cons and the choice depends on computer capacity, model purpose and user experience. Regarding temporal discretization one can distinguish predominantly between explicit and implicit techniques.

Coupling to hydrodynamics

Morphodynamic models are further categorized in decoupled, semi-coupled and fully coupled modelling types. Decoupled models neglect the influence of morphological changes on hydrodynamics by assuming small bed level changes and low sediment concentrations. In decoupled models first the hydrodynamic continuum and momentum equations are solved then the sediment continuity is solved by using the newly obtained flow variables. This asynchronous solution does not reflect the strong water-sediment interactions and its application is therefore limited (Cao et al., 2002). Fully coupled models solve all equation simultaneously and are physically more reasonable but require more computational efforts. Semi-coupled models compute some quantities in coupled form and others in separate forms. For instance Wu & Viera (2002) couple sediment load with bed level change and particle sorting but separate flow calculation from sediment calculation.

It should be noted that sediment-transport models might even be further classified in state of flows (steady versus quasi-steady or unsteady flow) or according to non-cohesive and cohesive particles that are not included in the previous classification. Given the wide range of different model concepts and strategies model users not only acquire detailed knowledge of the physical phenomena which are to be simulated, they also need to know how to conceptualize the phenomena in order to decide for the best fitting modelling type.

A.3.1.2 Mathematical description of sediment-transport

The use of computational models for solving morphodynamic processes involves the numerical solution of governing differential equations for water-sediment mixtures. As the focus is on the mathematical description of sediment-transport processes, the governing hydrodynamic equations are not discussed here. Although it is worth noting that the RANS-equation (Reynolds-averaged-Navier-Stokes Equation) are commonly applied to solve the hydrodynamics whereby different turbulence approaches are used to close the RANS- equations. The most popular ones are the Boussinesq's eddy viscosity concept, the Kolmolgorov-Prandtl expression or the k-ε-turbulence models. For a complete mathematical description of the hydrodynamic flow it is referred to the scientific literature (e.g. Wu, 2007).

Suspended load

The mathematical description of suspended load is driven by three main components: convection, diffusion and particle settling. The following Eq.A.3.1 demonstrates the three-dimensional transport function of suspended load which is also known as the convection-diffusion equation (closed with Boussinesq's eddy viscosity concept).

$$\frac{\partial c_S}{\partial t}+\frac{\partial(u_x c_S)}{\partial x}+\frac{\partial\left(u_y c_S\right)}{\partial y}+\frac{\partial(u_z c_S)}{\partial z}-\frac{\partial(\omega_s c_S)}{\partial z}=\varepsilon\frac{\partial^2 c_S}{\partial^2 x}+\varepsilon\frac{\partial^2 c_S}{\partial^2 y}+\varepsilon\frac{\partial^2 c_S}{\partial^2 z} \qquad \text{Eq.A.3.1}$$

Theoretically spoken is Eq.A.3.1 valid for all sediment loads in the entire water column (Wu, 2007) and could be solved directly by using the Rouse profile (see Chapter A.2.1.3). However as the sediment load is usually subdivided in suspended and bed load an extra boundary conditions is required in order to define the upward flux from the bed material. Eq.A.3.2 gives the boundary condition at the water surface defining the zero mass flux through the water surface and in Eq.A.3.3, which presents the boundary conditions at the interface between bed and suspended load.

Boundary condition on water surface:

$$\left(\varepsilon\frac{\partial c_S}{\partial z}+\omega_s c_S\right)=0 \qquad \text{Eq.A.3.2}$$

Boundary condition at the interface bed load/suspended load:

$$\left(\omega_s c_S+\varepsilon\frac{\partial c_S}{\partial z}\right)=D_B-E_B \qquad \text{Eq.A.3.3}$$

The boundary condition at the interface between suspended and bed load is applicable for both equilibrium and non-equilibrium transport. For equilibrium transport the entrainment rate E_B is equal to the deposition rate D_B. The near bed concentration is frequently set equal to the bed load concentration and is referred to as the reference concentration (Chapter A.1.3). Alternatively the boundary conditions can be defined as a function of specified exchange rates between suspended and bed load (Nelson et al., 2003). As an extension to the non-equilibrium approach formulated in Eq.A.3.3 some researchers developed probability functions into the deposition flux to account for the possibility that some near-bed suspended particles do not reach the bottom but get resuspended (e.g. Jankowski et al., 1994). Defining the sediment exchange between bed and suspended load has proven to be one of the most challenging problems in sediment-transport modelling (García, 2008).

Bed evolution

For the computation of bed change rates the Exner-equation which describes the sediment conservation is commonly applied. Concerning river morphodynamics the Exner-equation is the basis for all morphological developments of rivers and thus of major importance. The Exner-equation is represented in Eq.A.3.4.

$$\left(1-n_p\right)\frac{\partial z}{\partial t}+\nabla\overrightarrow{q_b}=D_B-E_B \qquad \text{Eq.A.3.4}$$

In general terms the Exner-equation describes the sediment continuity between sediments in the river bed and sediments in transport. It states that in case of erosion the bed level decrease in proportion to the amount of entrained sediments. In case of sedimentation the bed elevation increases in proportion to the amount of deposited sediments.

With regards to bed evolution algorithms one can distinguish between approaches using the total load and approaches considering the separation of bed and suspended load. The latter ones use the bed load control volume for interactions between bed level change and transported material.

Bed evolution processes can further be subdivided in equilibrium and non-equilibrium approaches. The widespread assumption about the equilibrium approach is an instantaneously adaption of bed level changes and transport rates to transport capacity. As previously mentioned this assumption is questionable because sediments in natural rivers cannot reach instantaneously equilibrium conditions due to temporal and spatial time lags between sediment and flow. Therefore a more general approach is the use of non-equilibrium models which introduce an adaptation length L for total load (Eq.A.3.5).

$$(1-n_p)\frac{\partial z}{\partial t}=\frac{1}{L}(q_b-q_{b*}) \qquad \text{Eq.A.3.5}$$

In Eq.A.3.5 all non-equilibrium effects are implied in the right-hand term which assumes a proportionality between non-equilibrium bed load q_b and equilibrium bed load q_{b*} that is related to the adaptation length L. The ratio of L to q_b or q_{b*} respectively represent the depositions and entrainment rates of bed load. In principle the adaptation length is based on the dimensions of sediment movements, bed forms and river topographies but in literature values are also obtained from the numerical mesh size (half or twice the element length, Bui & Rutschmann, 2010).

Bed load

The integration of Eq.A.3.1 over the bed load zone and the consideration of Eq.A.3.5 yields the following bed load transport equation load (Eq.A.3.6):

$$\frac{\partial}{\partial t}\left(\frac{q_b}{u_b}\right)+\frac{\partial(\alpha_{bx}q_b)}{\partial x}+\frac{\partial(\alpha_{by}q_b)}{\partial y}=\frac{1}{L}(q_b-q_{b*}) \qquad \text{Eq.A.3.6}$$

The variables α_{bx} and α_{by} are the cosines for transport direction of bed load rates (q_b) that could be influenced by secondary flow or gravity. In general the concentration at the bed load zone c_b is related to the bed load transport rate q_b which is obtained by the different bed load formulas (Chapter A.2.1.3) and the bed load velocity (u_b). As the bed load velocity is usually smaller than the flow velocity, Eq.A.3.6 accounts for the temporal lag between flow and sediment transport.

Non-uniform sediment transport

The interaction of particles in non-uniform sediment transport includes colliding, hiding, and particle exposure at the river bed. However, if the sediment concentration is low the interactions among moving particles might be negligible and it is assumed that the transport behaviour of each fraction is similar to uniform sediment transport (Wu, 2007). The following three equations describe the fractional sediment transport (size classes' j) for suspended (Eq.A.3.7) and bed load (Eq.A.3.8) as well as for bed level changes (non-equilibrium) Eq.A.3.9).

$$\frac{\partial c_{S_j}}{\partial t}+\frac{\partial(u_x c_{S,j})}{\partial x}+\frac{\partial(u_y c_{S,j})}{\partial y}+\frac{\partial(u_z c_{S,j})}{\partial z}-\frac{\partial(\omega_s c_{S,j})}{\partial z}=\varepsilon\left(\frac{\partial^2 c_{S,j}}{\partial^2 x}+\frac{\partial^2 c_{S,j}}{\partial^2 y}+\frac{\partial^2 c_{S,j}}{\partial^2 z}\right) \qquad \text{Eq. A.3.7}$$

$$\frac{\partial z}{\partial t}+\frac{\partial}{\partial t}\left(\frac{q_{bj}}{u_{bj}}\right)+\frac{\partial\left(\alpha_{bx}q_{bj}\right)}{\partial x}+\frac{\partial\left(\alpha_{by}q_{bj}\right)}{\partial y}=\frac{1}{L}(q_b-q_{b*})$$ Eq.A.3.8

$$\left(1-n_p\right)\left(\frac{\partial z}{\partial t}\right)_j=\frac{1}{L}\left(q_{b,j}-q_{b*,j}\right)$$ Eq.A.3.9

The total bed level change for j fractions is calculated by summing up the result of Eq.A.3.9 as it is shown in Eq.A.3.10:

$$\frac{\partial z}{\partial t}=\sum_{j=1}^{N}\left(\frac{\partial z}{\partial t}\right)_k$$ Eq.A.3.10

Bed material sorting

Particle size compositions in multiple layers:

The composition of bed material show vertical variations due to earlier and historical sedimentation events. Therefore, the bed material above a non-erodible layer is usually subdivided in one or multiple layers (Wu, 2007). Hirano (1971) first developed the concept of an active layer in which all particles exchange with those moving with flow (entrainment and deposition). Bennett und Nordin (1977) defined at least three layers; the lowest one has an indefinite depth while the subsurface layer (or active stratum) lies in between the lowest and the surface layer. The temporal variation of the bed-material gradation in the surface layer can be determined by solving the sediment continuity for each size class j as it is shown in Eq.A.3.11 (Bui & Rutschmann, 2010).

$$\left(1-n_p\right)\frac{\partial\left(\delta_{SL}p_{SL,j}\right)}{\partial t}+\nabla\overrightarrow{q_{bj}}=S_{F,j}$$ Eq.A.3.11

The right term $S_{F,j}$ in Eq.A.3.11 refers to the exchange rate of sediment particles between the surface and subsurface layer due to bed level changes. The variables $p_{SL,j}$ and δ_{SL} are the fractions of size class j in the surface layer and the surface layer thickness. The mass of a specific particle size class in the subsurface layer is only controlled by movements of the surface layer. This is expressed in Eq.A.3.12.

$$\left(1-n_p\right)\frac{\partial\left(\delta_{ML}p_{ML,j}\right)}{\partial t}=-S_{F,j}$$ Eq.A.3.12

The exchange source term $S_{F,j}$ in Eq.A.3.11 and Eq.A.3.12 gives for erosion the mass of the size class j, formerly comprising size fraction $p_{ML,j}$ of the subsurface layer which becomes part of the surface layer and in case of deposition $S_{F,j}$ gives the mass of size class j, formerly comprising to the surface layer, which becomes part of the subsurface layer. The thicknesses of the sediment layers significantly affect the sediment transport behaviour and determine the time-scale of morphological changes (Sloff & Mosselman, 2007).

Initial and boundary conditions for sediment transport

Next to the hydrodynamic initial and boundary conditions some sediment boundary conditions are required to solve the equations. For the upstream boundary condition (inflow) the sediment discharge has to be given for each fraction at each point of the inflow boundary.

This can be done either as a steady sediment discharge or as time-series. Usually, no outflow boundary is required (Wu, 2007). As initial conditions the river topography, suspended load concentrations and the bed material gradation for the entire model area have to be specified.

A.3.1.3 Limitations of morphodynamic modelling

Although tremendous progress has been made in computational modelling of hydro- and morphodynamics in the last decades there are still fundamental limitations in numerical modelling given to their empiric nature and numerous assumptions. Even in highly sophisticated models using fully three-dimensional computation, unstructured and adaptive grids, advanced turbulent approaches the implementation of sediment-transporting processes and morphological development is based on the following steps (Mosselman, 2010).

- division of sediment mixtures into separate particle fractions
- transport formula and sediment continuity for each particle fraction
- hiding/exposure correction of the critical shear stress
- division of the riverbed in multiple sediment layers

Sediment transport models using this classing approach include several limitations in describing the real natural physical processes. One shortcoming concerns the fact that many bed load formulas are developed for steady equilibrium conditions, whereas most sediment-transport models operate in an unsteady non-equilibrium environment (Spasojevic & Holly, 2008). Although the hidden and motion periods of particles including the lag coefficient for the movement of different size fractions has been recognized which led to the development of non-equilibrium formulas, the prediction of river bed evolution, the stability and adjustment to changing hydrodynamic forces is still a major challenge for state-of-the-art transport models (Nelson et al., 2003).

Very important in correct simulations of morphodynamic processes are the interactions between suspended load and river bed processes. Prevailing approaches rely on an empirical near-bed suspended concentration and on the excess shear stress term to compute sediment deposition and entrainment rates (García, 2008). This means that all local variables near the bed are captured in the bottom shear stresses. This assumption might be inadequate for two reasons: The first concerns near-bed turbulent sweeps. Outward interactions and ejections are important mechanisms regarding deposition and entrainment rates of particles (Papanicolaou et al., 2008). Another reason is the fact that, even if the bottom shear stress is close to zero, sediment-transport of fine material occurs in the interstices of gravel layers, (Nelson et al., 2003). Although small-scale turbulences can be simulated using direct numerical simulation (DNS) it is not an applicable method for river engineering problems (Rodi, 2006) as DNS requires enormous computing resources. A large eddy simulation (LES) solves the full 3D-Navier-Stokes equations on a high resolution grid with special algorithms for near-wall treatments and is currently the most advanced turbulence modelling tool (Mahesh et al., 2004). However, the high grid resolution in the range of the occurring turbulences is not applicable for simulating morphodynamic processes on larger scales.

Another limitation is that in most models the porosity is assumed to be constant. Processes like intrusion of fine sediment in gravel interstices with partial bridging and clogging effects are not considered in most sediment-transport models. In the sediment continuity equation these processes are difficult to consider as the filling and emptying of pores act as a temporary storage of sediment without changes of bed levels (Mosselman, 2010). A further distinction of sediment load in bed-structure load and pore-filling load – as suggested by Frings et al. (2008)

– might be helpful where bed-structure load is the coarse fraction interacting with bed structure and lead to bed level changes while the pore-filling-load is the fine fraction that infiltrates in the pores of the larger grains and do not result in any bed level changes. However, so far no sediment-transport model is available considering porosity without bed level changes. This becomes even more relevant in terms of sediment transport in-between the interstices of the river bed. This shortcoming is of special importance in this thesis as interstitial sediment dynamics with particle sorting between the different specified sediment layers strongly depends on varying porosities.

Additional questions arise concerning the thickness of sediment layers. According to García (2008) there is a kind of arbitrariness in the definition of the thickness of surface layers even it is an important parameter in sediment-transport modelling as model results demonstrated a high sensitivity to surface layer thicknesses (Wu, 2007). Most investigators developed empirical approaches related to flow, sediment conditions or bed deformations to define the surface layer thickness. As no physical description exists, it is often proposed to start with a thickness of the maximum particle diameter, the mean particle diameter or the saltation height and subsequently use the thickness as a calibration parameter in meaningful variations. According to Sloff & Mosselman (2007) the thickness determines the time-scale of mixing processes between the sediment layers whereby thin layers induces rapid morphological responses and thick layers slow morphological responses. Similarly, no rules or advices to specify the thickness of the intermediate layer can be found in literature. Frequently the thickness is defined according to the expected magnitude of sediment and erosion during the simulation time.

The formulation of sediment-flow interactions often neglects the stresses between fluid and sediment particles as these stresses are much smaller compared to turbulent stresses. Furthermore the interactions between solid particles are often not considered and it is assumed that sediment particles are not in contact with each other (Papanicolaou et al., 2008). However in case of high suspended concentrations and especially near the bed where the concentration is very high due to permanent entrainment and deposition of fine particles, these assumptions are questionable. Available approaches taking these effects into account are the adaptation of the settling velocities but a physical description of these sediment-flow interactions is not available.

Another major issue for proper simulating of morphodynamic processes is the definition of accurate boundary and initial conditions. Each sediment-transport model requires information about river geometry, distribution and composition of particle sizes as well as in- and outflowing sediment fluxes. The specification of sediment-fluxes for different fractions has often to be assumed as reliable data are not available (DVWK, 2003). The reliability of sediment-transport models always depends on the quality of measured data that are commonly used to derive initial and boundary conditions. For example the distributions of sediment mixtures in terms of vertical and horizontal variations as well as the variations in bed and suspended load are mentioned here because accurate measurements with a sufficient spatial resolution are difficult and very time- and labour-intensive. Hence, sampled data are frequently interpolated over characteristic areas that may not reflect the local heterogeneity of sediment characteristics in natural rivers. Consequently the degree of sophistication of morphodynamic tools cannot improve the simulation results when the quality of required input data is poor.

The description of morphodynamic processes for non-uniform sediment remains complex and available models are often too simplistic. Improvements may be derived from detailed measurements and experimental investigations that also require proper communication and coordination between researches involved in experimental and in numerical work. Other numerical methods like DNS or particle tracking methods might also contribute for further understanding and transformation of physical processes in numerical modelling schemes (Mosselman, 2010).

A.3.1.4 The Sediment-Transport Model SSIIM2

SSIIM is the abbreviation of **S**ediment **S**imulation **I**n **I**ntakes with **M**ultiblock option and is a three-dimensional CFD code, programmed in C-language, for simulating hydro- and morpho-dynamic processes. SSIIM is developed at the Department of Hydraulic and Environmental Engineering at the Norwegian Institute of Technology (NTNU; Olsen, 1991). The model has been developed for more than 20 years and started in 1990 with the first version, called SSII, which was programmed mainly due to the difficulty to simulate fine sediments in physical models. In 1993 SSII was advanced by adding a new water flow module for multi-block calculations leading to its final name SSIIM. In the following years further improvements and modules were added to SSIIM like a graphical user interface, an unstructured grid generation, a water quality module, a nested grid option, wetting and drying algorithms, multiple layers and parallel computing. Given the increasing sophistication of SSIIM the applicability is extended to many hydraulic/morphodynamic and environmental issues. One of the main strength compared to other CFD codes is the capability of simulating sediment transport processes with a moveable bed in a complex geometry (Olsen, 2010). This includes multiple sediment sizes, sorting, bed and suspended load, bed forms, effects of sloping beds and varying porosities. Additional to the internal graphic viewer SSIIM provide output-files for external software like TecPlot or ParaView for visualization purposes and post-processing.

Different versions of SSIIM

The program has been compiled on different operating systems, whereby the main user interface is made in Microsoft Windows. There are two main versions: SSIIM1 that uses a structured grid and SSIIM2 which is build on an unstructured grid. For both models, user interfaces are available for the Windows compiled versions. But alternatively both - SSIIM1 and SSIIM2 - can be run on Unix-systems without user interfaces. Further, it is possible to compile the program for 32- or 64-bits versions of Unix and Windows. This might be necessary when working with grids larger than 4 million elements as the 32-bit-version can only access 4 GB RAM while the 64-bit-version do not have this limitation (Olsen, 2010). Given to the parallelization of SSIIM even more different versions exist. Depending on the applied version only the hardcoded algorithms or additionally the dynamic link libraries (dll) are used, whereas the dlls contain additional features (e.g. vegetation, flow resistance, several sediment transport formulas, multiple sediment layers, cohesive sediments). In this thesis the SSIIM2 32-bit-version complied for Windows is used as well as the hardcoded 64bit-Unix Version to improve computational speed.

Structure of SSIIM

The main user interface of SSIIM2 consists of one window and provides different views including the grid editor, discharge editor, graphics and information about the convergence of the current simulation. The main menu offers also options to read required input files and to write result files for post-processing. An overview of the various in- and output files for SSIIM2 is given in Fig.A.3.1

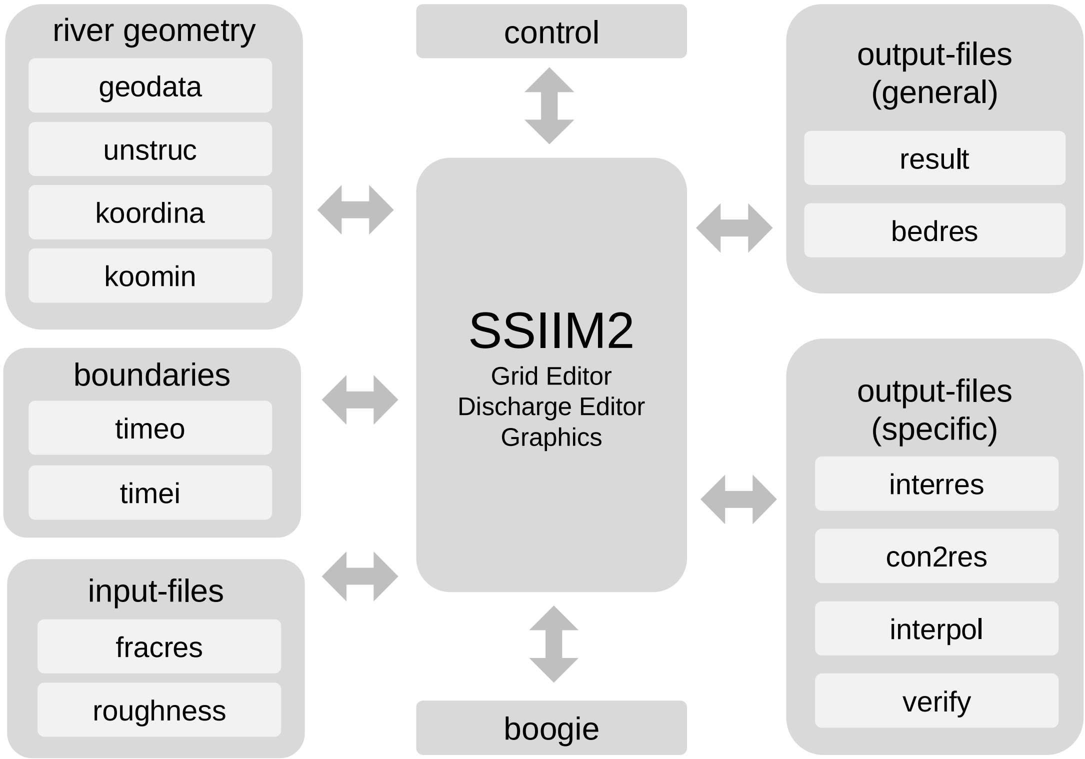


Figure A.3.1: Input and output files for hydro- and morphodynamic modelling in SSIIM2

The names of the files are fixed and cannot be changed. All in-and output files are in an ASCII-format and can be edited using standard text editors or spreadsheet software. The most important files are briefly explained below:

control: It contains most of the required variables for SSIIM2. Data sets, algorithms, numerical procedures, modules can be activated and deactivated using different capital letters that are followed by one or more numbers. The program reads each character of the file one by one and checks if all required variables are defined. An exemplary *control*-file is illustrated in Appendix 1.1.

timei and timeo: These files are relevant for unsteady simulations. The *timei*-file is an input file for time series of hydrodynamic and sediment boundary conditions (flow, water level, sediment concentrations) while the *timeo*-file is an output-file for time series of predefined variables on selected locations.

geodata, koordina, unstruc: These files represent the topography and the unstructured computational grid. The *geodata*-file contains the measured topographical points in the field and the *koordin*a-file gives the interpolated topography on the computational grid and the initial water surface elevation. In the *unstru*c-file the whole grid information is stored containing coordinates of all grid intersections and defines how elements and element surfaces are connected to each other. Furthermore it contains information about the locations of open boundaries where input data is required.

fracres, roughness: Both files are input files. The *fracres*-file contains spatial distribution of fractional percentages of the initial particle size distributions and the thicknesses of the applied sediment layers. The r*oughness*-file contains the spatial distribution or varying roughness values.

bedres: This file is an output file and contains information about the particle size distributions, bed level changes, layer thicknesses and roughness's. For unsteady simulations a series of *bedres*-files can be written to obtain intermediate results. Further the *bedres*-file can be read by SSIIM2 to create graphical outputs but also to proceed with a simulation from a previous time-step (‘hotstart’).

result: It is also an output file and contains the results from hydrodynamic simulations and provides input for morphologic modelling. Similarly to the *bedres*-files, series of *result*-files can be written and be used either as a ‘hotstart’ or to proceed a calculation from a previous time-step.

boogie: The major purpose of this file is to get information about computational errors. When SSIIM terminates error messages are written in this file. Next to these error messages it contains information about the occupied computer memory, the convergence and simulation results.

Grid generation

Grid generation in SSIIM2 is done using the grid editor of the main user interface. Several options for grid generation are available. The grid type in SSIIM2 is an unstructured adaptive one which means that the shape of elements can be both triangular and quadrilateral (unstructured) and that the grid allows vertical adaptations due to changes of water depth (adaptive). SSIIM2 offers also the use of nested grids which means to implement a grid with smaller elements into a grid of coarser elements to increase the grid resolution over a certain area. To improve the grid quality in terms of numerical convergence the orthogonality can be improved using transfinite or elliptic interpolations to create internal grid nodes.

Fig.A.3.2 illustrate exemplary a grid cell distribution of SSIIM2 in a profile view (A) and in a plan view (B).

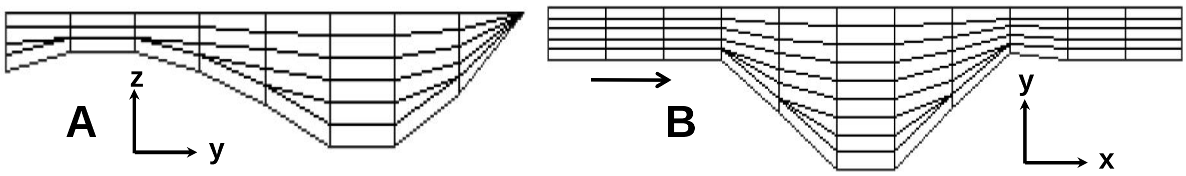


Figure A.3.2: Exemplary distribution of grid cells using the unstructured grid of SSIIM2. (A) a profile view, (B) a plan view (from Olsen, 2010)

The cells have a tetrahedral and hexahedral shape to adapt most accurately to the river shape and bed topography. Especially for sediment-transport processes an exact replica of the river bed topography is required as most of the sediment is transported close to the bed (Olsen, 2010). It is possible in SSIIM2 to have varying numbers of grid cells in the vertical direction with different shapes according to the topography. The number of vertical grid cells is a function of water depth and can be specified in the *control*-file. Thus, the use of unstructured adaptive grids in SSIIM2 enables a high-detailed reproduction of complex river geometries which is absolutely necessary in simulating hydro- and morphodynamic processes for micro-scale studies.

Water flow calculation

SSIIM2 solves the three-dimensional RANS-equations on a three-dimensional grid. When using the default-values the RANS-equations are closed using the k-ε-turbulence model (Rodi, 1980). This can be modified to a range of different turbulence models (e.g. eddy viscosity, k-ω-model). The momentum equations are in their complete form, without resorting to the hydrostatic assumption. The free water surface is computed using the pressure and

Bernoulli algorithm. This method is based on the computed pressure field and uses the Bernoulli equation along the water surface to compute the water surface location starting from a fixed point. To consider the steep gradient of flow next to closed boundaries without resolving the grid in many small elements the wall law of Schlichting (1979) is implemented in SSIIM2. Furthermore, SSIIM2 offers an opportunity to account for the influence of sediment concentration on the water flow. Generally these are two processes: Firstly, the sediment close to the river bed that is moved by jumping and settling causing a reduction of flow velocity near the bed as some energy is used for the sediment movements. Secondly, sediment concentration might increase the water flow density and thus changing the flow characteristics. In the default model set-up these effects are neglected but algorithms are available to change the velocity profile according to the influence of sediment concentrations.

Sediment flow calculation

SSIIM2 calculates sediment transport by size fractions in multiple sediment layers. For suspended load SSIIM2 solves the convection-diffusion equation (Eq.A.3.1) whereby the diffusion coefficient is taken from the k-ε-turbulence model. In SSIIM2 the calculated sediment concentration is fixed to the element closest to the river bed. It is also possible to convert the sediment concentration in an entrainment rate that might be applied for time-dependent computations (Olsen, 2010). The sediment concentration for suspended and bed load can be calculated using several transport-formulas (e.g. van Rijn (1984), Engelund & Hanson (1967), Ackers & White (1973), Yang (1984), Einstein (1950), Wu et al. (2000)) and in the *control*-file many empirical parameters and coefficients can be modified for model calibration purposes. However, if completely different formulas are to be used, the user has the possibility to implement the special formula in a dll-file (beddll) which provides basic sediment transport functions that can be read by SSIIM2. Furthermore, SSIIM2 offers many possibilities to adapt and modify sediment transport processes by specifying various algorithms in the *control*-file. Examples are varying degrees of sediment compactions, the Hunter-Rouse sediment distribution, various Schmidt-numbers for multiple particle sizes, sloping bed effects, bed smooth algorithms, cohesive transport processes or different hiding/exposure algorithms. In SSIIM bed material is sorted by considering the sediment continuity for each fraction whereby the thickness of the active layer remain constant (Ruether, 2006). A recent development of SSIIM2 allows simulating particle sorting considering various porosities which is essential for the simulation of interstitial sediment dynamics.

Numerical transformation

The transformation of the differential equations into a form where the variable of one element is a function of the neighbouring elements is done by numerical discretization. SSIIM solves all differential equations using the finite volume method (FVM) which is based on the continuity of flow and sediments meaning that the sum of all in- and outgoing fluxes over all element surfaces is zero (Olsen, 2010). The convective terms can be solved using the power-law or the first and second order upwind scheme, while the unknown pressure field is solved using the SIMPLE-method (Patankar, 1980). SIMPLE is the abbreviation for 'Semi-Implicit Method for Pressure-Linked Equations' and solve the unknown pressure field iteratively based on the continuity defect. The transient term is solved using an implicit discretization scheme allowing longer time-steps compared to explicit methods.

Although SSIIM has proven its universal character in many widespread applications (Ruether, 2006) it is stated by the developers that the program is made for teaching and research purposes and might not be as well tested as commercial programs (Olsen, 2010).

A.3.2 Aquatic Habitat Modelling

A.3.2.1 General aspects of aquatic habitat modelling

Importance of aquatic habitat modelling tools

In order to quantify and predict ecological impacts, aquatic habitat simulation tools have been used for decades in water resources management. One of the first available physical habitat models was PHABSIM (Bovee, 1982; Milhous et al., 1989) as a component of the Instream Flow Incremental Methodology (IFIM, Bovee, 1982; Stalnaker, 1995) that was developed in North America. In the 1980s physical habitat models became an important tool for river management (Bockelmann et al., 2004) and nowadays they are applied worldwide. Moreover, they are still in the focus of ongoing debate and research and today a great variety of different model types and techniques have been developed encompassing nearly all types of aquatic organisms.

These physical habitat models use so-called physical-biota relationships (Conallin et al., 2010) which represent the core in predictive habitat modelling as they aim to assess how environmental factors control the distribution of species and communities. Although many studies have assessed the biotic response to altered environmental conditions, there is still a clear need of quantifying these species-environmental relationships (Guisan & Zimmermann, 2000). Physical habitat modelling tools allow for such quantifications as they predict habitat quality in relation to the physically described environment. From a more practical point of view, water resources managers require methods and tools to quantify the disturbance level of ecosystems compared to a reference state. For choosing among the available modelling approaches water managers have to compromise between model performance itself, policy, finances, scale and data requirement (Conallin et al., 2010).

Data sampling and habitat variables

As data sampling and the quality of habitat simulation influences each other significantly, a conceptual model with prioritisation of dominant habitat variables might be helpful to obtain an efficient sampling and modelling strategy (Mouton, 2008). Hence the first step is to identify all relevant parameters that are required to describe the abiotic features of the environment which are necessary for survival of target species (Rosenfeld, 2003). Since experiences in fish habitat modelling have been assembled over decades a high level of knowledge about relevant habitat variables is already available (Hardy, 1998; Souchon & Capra, 2004). The most applied and so called conventional variables in physical fish habitat modelling are flow velocity, water depth and substratum (Bovee, 1982; Heggenes, 1988). However, the selection of input parameters can vary from case to case and in recent research these classical parameters are rarely applied solely but combined with additional parameters to get a more realistic picture of the abiotic environment (Noack et al., 2005; Schneider et al., 2007, Wieprecht et al., 2006).

To conduct a study, an appropriate spatial scale had to be chosen that fits to the modelling purpose and defines the choice of governing parameters. Maddock (1999) divides the spatial scale into macro-, meso- and microhabitats and so far most physical habitat approaches are applied for simulating microhabitats as they are linked to detailed hydrodynamic or morphodynamic models (Kopecki, 2008). As detailed habitat investigation on micro-scale can be cost- and labour intensive, several mesohabitat approaches have been developed (e.g. MesoHABSIM, MesoCASiMiR; Parasiewicz & Walker, 2007; Mouton et al., 2006) as an intermediate method between the large river management scale (macro-scale) and the detailed micro-scale.

Next to the spatial scale, aquatic habitat simulation also depends on the temporal scale and there are several aspects that have to be considered, for example seasonality, diurnal characteristics of species but also the choice of the sampling period, the frequency and duration of sampling or different life-stages of the target species. Moreover, abiotic temporal characteristics like the natural flow variability and disturbance frequency (Poff et al., 1997) affect habitat quality. For detailed information, the COST Action 626 report: "State-of-the-Art in data sampling, modelling analysis and application of river habitat modelling" provides a classification of appropriate variables corresponding to spatial-temporal scales.

The principle functionality of physical habitat modelling

As physical habitat is a key factor in evaluating the ecological status of rivers (Chapter A.2.2, Maddock, 1999), the classical approach of quantifying habitats consists of estimating habitat indices regarding an optimum range of abiotic conditions for indicator species (Leclerc et al., 2003). Based on a comparison of existing abiotic conditions and preferred abiotic conditions of aquatic organisms, a habitat quality is yielded for a certain location. The most common index to describe biological response is the habitat suitability index (HSI) ranging from 0.0 (unsuitable) to 1.0 (most suitable). Concerning the linkage between biotic response and abiotic factors different approaches are applied. They can mainly be classified in univariate methods which consider habitat variables individually or multivariate approaches which account for interactions of habitat variables to determine the species response for cumulative effects. Based on the HSI-values the weighted usable area (WUA) or the hydraulic-habitat-index (HHS, Stalnaker et al., 1995) of a species can be estimated as a function of the flow rate (Gore & Nestler, 1988). The formulas to calculate WUA and HHS are presented in Eq.A.3.13 and Eq.A.3.14, respectively.

$$WUA = \sum_{i=1}^{n} A_i \cdot HSI_i = f(Q) \qquad \text{Eq.A.3.13}$$

$$HHS = \frac{1}{A_{total}} \sum_{i=1}^{n} A_i \cdot HSI_i = f(Q) \qquad \text{Eq.A.3.14}$$

In the case that all aerial elements have optimal habitat suitability (HSI=1.0) the WUA would correspond to the wetted area. Characteristically the WUA increases up to an optimum flow and then decreases as discharge becomes too high and the habitat variables are out of the preferred ranges of the considered species. The HHS divides the WUA by the wetted area leading to an index ranging from 0.0 to 1.0. The HHS eliminates the influence of the wetted area and enables a better comparison between study-sites that have different spatial scales.

According to Conallin et al. (2010) aquatic habitat modelling tools can be used to

- identify individual biota-physical habitat relationships,
- assess the quality of the physical habitat variables through impact on the biota,
- predict likely biological responses if hydromorphological changes to a system occur.

In the literature several reviews about existing habitat modelling techniques can be found, (e.g. Rosenfeld et al., 2003; Harby et al., 2004; Ahmadi-Nedushan et al., 2006; Conallin et al., 2010).

A.3.2.2 Modelling techniques in physical habitat modelling

Preference functions

Univariate preference curves are the simplest and most applied habitat suitability functions and can be derived from three different types (Bovee, 1998; Parasiewicz & Dunbar, 2001, Harby et al., 2004): Category I – expert judgement indices, Category II – habitat use indices and Category III – habitat preference indices. Category I indices are derived from life history studies in literature or expert opinion while Category II indices are based on data that are specifically collected for habitat studies e.g. frequency analysis of habitat conditions used by indicator species. Category III indices combines the measured habitat use of Category II with additional information on measured habitat availability using e.g. the Jacobs selectivity index (Jacobs, 1974) or the forage ratio (Edmondson & Winberg, 1971).

The results of physical habitat modelling using univariate preference functions are individual HSI-values for specific habitat variables and have to be combined (Vadas & Orth, 2001) to a composite suitability index (CSI) using mathematical operations like the product method, the arithmetic mean, the geometric mean or the minimum method (Schneider, 2001).

Product Method: $$CSI = \prod_{i=1}^{n} HSI_i \quad \text{Eq.A.3.15}$$

Arithmetic Mean Method: $$CSI = \frac{\sum_{i=1}^{n} HSI_i}{n} \quad \text{Eq.A.3.16}$$

Geometric Mean Method: $$CSI = \left(\prod_{i=1}^{n} HSI_i\right)^{\frac{1}{n}} \quad \text{Eq.A.3.17}$$

Minimum Method: $$CSI = \min\left(HSI_i \ldots HSI_n\right) \quad \text{Eq.A.3.18}$$

The most applied approach is the product method (Ahmadi-Nedushan et al., 2006) which is based on the assumption that fish selects each particular variable independently of other variables (Bovee, 1986). Using the arithmetic mean, variables with a high quality of single HSI-values can compensate for poor HSI-values of other variables as it takes the average of all single HSI-numbers. The geometric mean calculates the n^{th} root of the product on n individual indices that also implies some compensation but similar to the product method yields zero if one of the variables gets HSI-values of zero. The minimum method assumes that the lowest HSI defines the upper limit of CSI and is based on the fact that high-quality HSI-values of one variable cannot be compensated by another variable. These mathematical operations to combine individual HSI-values to a CSI are based on two major assumptions: the independency of all variables (Beecher et al., 2002) and the equal importance of all variables.

These assumptions are the foundation of most criticism for univariate approaches. Especially the fact that mathematical methods to combine single HSI-values do not consider parameter interactions (Bain, 1995, Jowett, 2003; Leclerc et al., 2003) and that the assumption of independent variables is inadequate as in reality these variables are not independent (Ahmadi-Nedushan et al. 2006). Moreover, the CSI-values calculated with different mathematical methods (based on the same single HSI-values) lead to a wide range of different results and lack any biological meaning (Noack et al., 2010). To compensate these limitations several new methods have been developed to combine individual HSI-values. One way is to superpose results of various simulation runs using different sets of univariate preference curves or to apply multivariate exponential functions to describe preferences of species. Advantages of using preference functions are their ability to deal with many data types simultaneously and that they have been tested in many studies for different biota groups. Given to two decades of applications there is a profound experience available in applying preference functions and several user-friendly models have been developed.

Fuzzy-rule based approaches

Fuzzy-logic (Zadeh, 1965) is a multivariate approach and means to work with imprecise (fuzzy-) information. The basic element of fuzzy-logic systems are overlapping membership functions describing all habitat variables as well as the output (HSI) in linguistic variables (e.g. ‘low’, ‘medium’ or ‘high’). The membership functions are linked via a fuzzy-rule system to HSI-values. A fuzzy-rule in form of an IF-THEN-rule defines the relation between input variables and their consequence that is in case of habitat modelling the habitat suitability index. The rules are automatically weighted according to the degree how well a rule reflects the combination of input parameter (Schneider, 2001). The significant advantage is that expert knowledge which is readily available from experienced fish biologists can easily be transferred into fuzzy-sets and corresponding rules by setting up check-lists with possible combinations of relevant physical criteria. Hence, fish experts define if habitat quality is ‘high’, ‘medium’ or ‘low’. This way of definition coincides well with ecological issues as impacts of ecological coherences cannot be described in exact functions or equations, but quite well be estimated. Fuzzy-logic has proven to be an appropriate modelling technique to deal with ecological gradients because the boundaries between the parameter classes are overlapping und thus can reflect these gradual transitions (Salski, 1992; Mouton, 2008). The better use of uncertain data makes the fuzzy-approach more appealing compared to the preference functions, especially in poor-data situations (Adriaenssens et al., 2004; Conallin et al., 2010). The major criticism of fuzzy-approach in ecological modelling is the dependency on expert-knowledge and the corresponding subjectivity (Acreman & Dunbar, 2004; Mouton, 2008). A more detailed description of the fuzzy-logical approach is given in Chapter A.3.2.4.

Multivariate statistical methods

In the last two decades the applications of multivariate statistical methods to investigate biota-physical relationships - especially regression methods - has been increased. Generally, regression techniques associates independent and dependent habitat variables in order to relate a response variable (e.g. HSI, abundance) to a single (simple regression) or a combination (multiple regression) of habitat variables (Ahmadi-Nedhusan et al., 2006).

<u>Multiple linear regressions (MLR):</u>

MLR for habitat simulation purposes use response data to relate habitat qualities with multiple habitat variables to find the best fitting model describing the relation between species response and a set of habitat variables. To estimate regression coefficients commonly the ordinary least squares (OSL) algorithm is applied in minimizing the deviances between predicted and observed responses. If no linear relations between response and habitat variable are found, polynomial regression techniques might be a solution where higher order terms allow simulating skewed and bimodal responses (Guisan & Zimmermann at al., 2000). One general problem in MLR is multicollinearity leading to unstable regression coefficients and large standard errors as habitat variables are intercorrelated (Armstrong et al., 2003).

<u>Logistic regressions (LR):</u>

LR is a multivariate linear technique that is applied to investigate the relationship of abiotic variables to a binary biotic response (e.g. presence/absence of species, Jongman et al., 1995). The LR-model estimates the probability of a positive response depending on a certain set of habitat variables. The maximum likelihood method is generally used for estimating the coefficients of logistic regression models. LR allows dealing with categorical and continuous variables simultaneously and also has been widely applied in the field of habitat modelling (Geist et al., 2000; Garland et al. 2002) but also for obtaining habitat suitability functions by evaluating the probability of occurrence against single habitat variables (Schmutz et al., 1999).

<u>Generalized linear models (GLM):</u>

A GLM allows the response variable to have other distributions than the normal distribution (e.g. binomial, Poisson etc.) but transformation functions are used to achieve a linear dependency of the habitat variables. A GLM is comprised of a response variable distribution, a linear predictor which defines the habitat variables and a transformation function describing the relation between the linear predictor and the expected response variable. According to Ahmadi-Nedhusan et al. (2006) GLMs are more flexible for analysing physical-biota relationships (compared to MLR) as they not depend on input data that is normally distributed. However they are not widely used in physical habitat modelling so far (Conallin et al., 2010; Ahmadi-Nedhusan et al., 2006).

Non-parametric models

According to the continuum theory (Oksanen & Minchin, 2002) and the ecological niche theory (Chase & Leibold, 2002) a linear response is not always appropriate and a non-linear response might be required. If the assumptions of parametric regressions like normally distributed data or linear dependency do not hold, then non-parametric techniques might be an alternative modelling technique. Two methods gaining attractiveness are the general additive model (GAM, Jowett & Davey, 2007) and the multivariate adaptive regression splines (MARS, Leathwick et al., 2005). According to Lehmann et al., (2002) GAMs are an extension of the GLMs, as GAMs estimate response curves with non-parametric smooth functions instead of parametric terms. Following this, it can be stated that GAMs allow any shape (highly non-linear and non-monotonic) to relate the response variable to the independent habitat variables as long as the function is additive and the components are smooth (Guisan & Zimmermann, 2002). Therefore GAMs provide more flexibility in biota-physical relationships and may lead to an increased understanding of ecological systems (Amhadi-Nedushan et al., 2006). The MARS-models are analogous to GAMs but they subdivide the input space into regions whereby each of the regions is represented by its own regression equation. One of the main problems dealing with GAMs and MARS is the large amount of data that is required to make their use worthwhile (Barry & Elith, 2006).

Artificial neural networks (ANN)

ANNs are non-linear mapping structures similar to the way a human brain works (Lek et al., 1996; May et al., 2008). ANNs receive increasing attention in ecological studies (Olden & Jackson, 2002) as they are able to deal with non-linearity, complex, noisy and multivariate data. Further, they are able to learn and adapt incorporated processes (Conallin et al., 2010). ANNs consist of nodes or neurons representing, a set of processing elements that are connected to each other, and corresponding training algorithms. A trained ANN is able to identify and generalize relationships between in- and output data and gives predictions for new inputs that were not part of the training data set. Several types and techniques of ANNs are applied. One widely approach used is the multi-layer feed-forward network which consists of at least three layers: an input layer, one or several hidden layers and one output-layer. While the input layer consists of the chosen habitat variables, neurons and a bias node for training effects, the hidden layer is the locations where the network is trained. In a feed forward network a training set, consisting of exemplary in- and output cases, is used to adapt the weights and biases of the network connections until the output cases fit to the example cases. Although there are various learning algorithm, a widely applied one is the back propagation method (Fine, 1999). Applications of ANNs have been reported since 1990 and were successfully applied in modelling species richness, density or biomass (Gozlan et al., 1999; Park et al., 2006) as well as for fish habitats (Brosse & Lek, 2002). However, ANNs have been criticized in terms of their explanatory value (black-box) (Olden & Jackson, 2002) and the large amount of required data sets for training. This is a problem as ecological data are often limited leading to too small training data sets (Lek & Guegan, 1999) and subsequently to poor simulation results.

Individual (agent)-based modelling approaches (IBM)

IBMs are a more biologic-related alternative to physical habitat modelling. The intention of using IBMs is to take individual variability into account that is neglected by state variable models (Grimm, 1999) as individuals are adaptive in terms of growing, developing, acquiring resources and interacting with the environment. IBMs are based on the assumption that the individual selects habitats to maximize their potential fitness by executing certain behaviour in relation to their interactions with the environment (Conallin et al., 2010). This approach differs from aforementioned habitat models as IBMs attempt to capture dominant biological processes like growth, survival, behaviour or fecundity and investigate how these factors are affected by river flow (Grimm & Railsback, 2005). Similar to the fuzzy-logic approach IBMs use simple rules (IF-THEN) to simulate complex behavioural responses to changes in the habitat variables (Railsback & Harvey, 2002). Basically, IBMs can be distinguished in biological process-based models that are an extension to conventional physical habitat modelling but considering additionally factors like food availability, foraging behaviour or metabolic processes to simulate habitat suitability (Hayes et al., 2000) and bioenergetic models that comprise a suite of metabolic equations to quantify functional relationships between bioenergetic parameters like water temperature, growth data, energy density, digestion based on energy as a unit (Elliott, 1976). As IBMs are working on a disaggregated level, the level of detail involves the description of a high number of attributes and behaviours with interactions that can only be handled by multiple simulation runs with systematically varying initial conditions or parameters to achieve a certain robustness of results which is a time-consuming process. Another criticism is that IBMs are more difficult to analyze, to understand and to communicate than other aquatic habitat modelling approaches as it is difficult to provide detailed descriptions of the inner workings of such models (Grimm, 1999).

A.3.2.3 General limitations in physical habitat modelling

The focus of this section is not to present the criticism and limitations of the varying aquatic habitat modelling techniques itself but to provide an overview of the limitations of physical habitat modelling in general. As models are always simplified representations of nature the critical factors and limitations of a modelling approach have to be known by the applying person for a correct interpretation of the results. This is especially important in aquatic habitat modelling as on the one hand aquatic ecological systems are characterized by enormous complexity and on the other hand ecological data often shows a high bias and uncertainty.

Biological interactions

The objective of aquatic habitat modelling is the reflection of changing environmental variables in biota. The choice of habitat variables consists mainly of abiotic habitat factors like water depth, flow velocity, substrate conditions, cover, temperature, dissolved oxygen and many others. None of the aforementioned modelling approaches (except of IBMs) consider directly real biological factors and interactions like predator pressure, growth, metabolic processes, energy budget, assimilation or nutrient availability which can also strongly influence habitat quality and habitat choice of aquatic species (Gordon et al., 2004). The complex system with interactions between biological parameters itself and the influence of abiotic parameter on biological processes constitute an extreme challenge for quantitative habitat modelling (Harby et al., 2004). IBMs are attempted to deal with these processes but the current understanding of all these mechanism including all interactions is also a challenge for current biological research and a lot of effort is invested to improve the knowledge about these biological interactions.

Fluvial dynamic processes

So far, more or less all aquatic habitat models are focused on steady-state investigations of habitat qualities and neglect the effects of fluvial river dynamic processes on potential fish habitats (Brodeur et al., 2004; Pasternack et al., 2004; Gard, 2006; Wieprecht et al., 2006). On the one hand the hydraulic parameter water depth and flow velocity are considered dynamically by hydrodynamic-numerical models, but on the other hand the distribution and composition of substrate conditions is assumed to be static and morphodynamic changes like erosion, sedimentation, armouring, scouring or colmation are not considered in habitat modelling. However, as described in Chapter A.2.2.5 and A.2.3.3 morphodynamic changes are of crucial importance in determining the present suitability and serviceability of fish habitats. In particular for the reproduction of gravel-spawning fish the continuously changing habitat conditions play a major role in assessing habitat quality as eggs and larvae react highly sensitive to any morphodynamic processes during incubation. With the static conventional habitat variables and modelling types these dynamic changes are not considered. Therefore, it is necessary to account for both the temporal variability of morphologic changes and the integration of additional parameters to describe these processes. According to Kirchhofer (2001) bed load dynamics are among the most important processes to provide habitats for biodiversity in flora and fauna and in recent research sediment dynamics are gaining more popularity in determining fish habitats (Noack, et al., 2008; Hauer et al., 2008; Wheaton et al., 2010; see also Part B, Chapter B.2.1).

Habitat preferences

Each aquatic habitat simulation tool requires habitat preferences of target species to express the biological response to a certain choice of habitat variables. One significant source of error in applying physical habitat modelling techniques is the incorrect use of biota-physical relationships, mostly due to transferring preferences from one area to another without adequate testing of transferability (Conallin et al., 2010). Ideally habitat preferences should be developed site-specific (Heggenes, 1990) as factors influencing fish habitat vary locally and fish are adapted to these specific local conditions in rivers (Moir et al., 2005). Another point is the temporal variation of habitat preferences. Fish behaviour and habitat use can shift from day to night (light conditions) as well as in seasonal patterns (temperature conditions). Hence, for reliable physical habitat modelling, habitat preferences have to be developed not only on the base of life-stages but also on the usage of habitats considering seasonal and diurnal patterns. In literature, some regional or general habitat preferences exist (e.g. Souchon &

Capra, 2004) that might be adapted to each local condition when applying them but no standard method is available regarding the transferability of habitat. In many practical applications general habitat preferences are applied for two major reasons: Firstly, the development of habitat preferences on a site-by-site basis is costly and labour-intensive and secondly in heavily artificial impacted streams the ecological conditions are very poor and not enough data is available to create specific local habitat preferences.

Interpretation of results

Often the results of physical habitat modelling tools are interpreted to obtain information about the ecological condition of aquatic ecosystems in terms of habitat suitability and WUA for selected indicator species. But the conclusion from habitat supply to an ecological condition is weak as there are many other factors influencing ecological functionality. According to Milhous (1999) physical habitat is a necessary but not a sufficient condition for the existence of species. Moreover pure physical habitat predictions cannot be compared to fish populations or fish abundance as habitat choice and therefore the location of fish may be dominated by factors not considered as habitat variables (e.g. biological interactions, Gordon et al., 2004). Moreover, little information is known about how much habitat suitability or WUA is required to represent population dynamics expressed in biomass or abundance. Moreover, the assumption ‘if habitat is maintained then fish population is maintained’ is also quite weak as interactions between life-stages and potential limits of habitat supply are not considered (Gore & Nestler, 1988; Irvine et al., 1987; Gordon et al., 2004). Therefore, care has to be taken when interpreting the obtained results of habitat modelling for ecological assessments.

A.3.2.4 CASiMiR: a multivariate fuzzy-approach for habitat modelling

Fuzzy theory and the physical habitat model CASiMiR

The fuzzy-set theory was developed by Zadeh in 1965 and assumes that complex systems are characterized by imprecise transitions between different states of a system. Contrary to the Boolean logic, fuzzy-logic allows systems to be in intermediary states which is especially in ecological modelling of high importance as transitions in ecology are not crisp but gradual (Salski, 2002; Cadenasso et al., 2003). The fuzzy-logic has proven to be an excellent modelling technique to deal with ecological gradients as the overlapping fuzzy-set theory reflects these gradual transitions between predefined classes (van Broekhoven et al., 2006; Mouton, 2008).

As fuzzy-logic has distinctive advantages compared to classical modelling techniques the Institute for Modelling Hydraulic and Environmental Systems (IWS) of the University of Stuttgart developed the first physical habitat model incorporating a fuzzy-approach, called CASiMiR (Jorde 1996; Schneider 2001). Originally, it was designed as a habitat model to facilitate the investigation of riverine habitat suitability for fish and macrozoobenthos in terms of habitat suitability/availability and to assess minimum flow criteria but nowadays it has been advanced to a wide range of applications in ecohydraulic research and management (e.g. revitalization measures, effects of hydropeaking or the impacts of reservoir flushing processes, riparian vegetation). The open structure of CASiMiR allows linkages to any multidimensional hydro- and morphodynamic modelling tools which are able to predict the abiotic environmental parameters. This makes CASiMiR to an appropriate modelling tool to simulate the reproduction of gravel spawning. The next section describes the functionality of CASiMiR and its multivariate fuzzy-approach consisting of four main parts (Fuzzification, Rule-System, Inference Method and Defuzzification).

Fuzzification

The first step in fuzzy-modelling is the fuzzification of the chosen habitat variables by defining overlapping membership functions in order to describe their parameter ranges. This process defines real numbers between 0.0 and 1.0, where 0.0 means that an element does not belong to a membership function while 1.0 means that it belongs entirely. Usually, a habitat variable is subdivided into several membership functions which are described by linguistic variables (e.g. ‘low’, ‘medium’ or ‘high’) forming a set of membership functions. The whole parameter range is not only defined by the physical values observed in the field but also by the ranges that a target species use. Although a membership function can be described by any function, mainly simple trapezoidal (described by four values: $a_1 \dots a_4$) or triangular functions are applied for defining fuzzy-sets, whereby triangular functions are a special case of trapezoidal functions ($a_2 = a_3$) as it is shown exemplary for the habitat variable flow velocity in Fig.A.3.3.

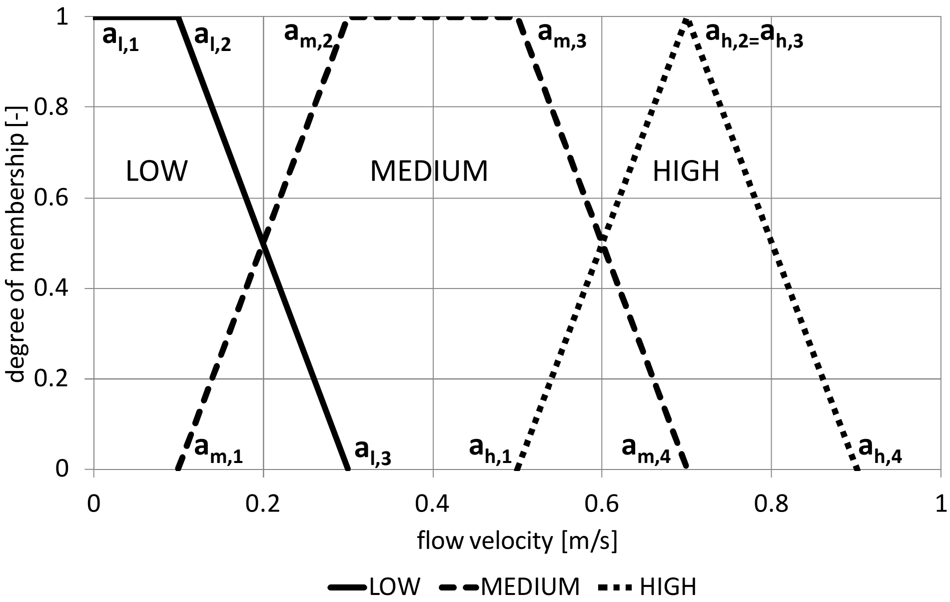


Figure A.3.3: Example of defining triangular and trapezoidal membership functions for the habitat variable flow velocity (fuzzification)

Given the overlapping membership functions which reflect gradual transitions between parameter classes the fuzzy-theory allows an appropriate representation of ecological gradients. For example, a particular fish may not differentiate between flow velocities between 0.19 m/s or 0.21 m/s and the fuzzy description that use partly ‘LOW’ and partly ‘MEDIUM’ flow velocities more closely approximate the ecological gradients which fish tends to follow (Adriaenssens et al., 2004).

Fuzzy rule-system

After fuzzification the physical-biota relationships have to be determined using IF-THEN rules. A fuzzy rule consists of several arguments (habitat variables) building a premise in the first part and a consequence (HSI) in the second part. This procedure has the significant advantage that expert knowledge can easily be transferred into preference data sets and combinations of relevant physical criteria can be addressed. Hence, the experts themselves define the conditions under which habitat quality can be described as ‘high’, ‘medium’ or ‘low’. E.g. if information like “these fish seem to avoid deep water” is available this could be transferred to the rule:

IF water depth is ‘HIGH’ *THEN* habitat quality is ‘LOW’

Tab.A.3.1 gives exemplary a rule-set describing the habitat requirements of spawning brown trout.

Table A.3.1: Exemplary fuzzy-rules describing the habitat requirements of spawning brown trout

	vel	**dep**	**sub**	**HSI**	Examples:		
1	L			L	rule 1	IF velocity "Low" THEN HSI "Low"	
2		H		L	rule 2	IF depth "High" THEN HSI "Low"	
3	M or H	L	M	M	rule 3	IF velocity "Medium" or "High" AND depth "Low" AND	
4	M or H	L	L	L	vel	= velocity	L = Low
5	M or H	M	M	H	dep	= water depth	M = Medium
6	M or H	M	H	H	sub	= substratum	H = High
7	M or H	H	H	H	HSI	= habitat suitability index	

For any possible combination of habitat characteristics the total number of rules - which has to be provided - depends on the number of input variables (vel, dep, sub) and membership functions (L, M, H). The ability to define complex physical-biota relationships as a series of simple IF-THEN rules corresponds to the simulation of imprecise problems that commonly arise in ecological modelling. Moreover, the verbal formulation of the rules closely resembles human communication that is important to transfer simulation results to river managers and other stakeholders (Ahmadi-Nedushan et al., 2008).

Inference System

For a fuzzy-simulation the inference-processor runs systematically through the entire set of rules and determines the degree of fulfilment (DOF) depending on the combination of input variables. The better the rule reflects the habitat parameters the higher the DOF. Usually several rules have a DOF>0, or in other words are partly true and subsequently become activated to calculate the HSI of a certain location. They have to be combined in order to receive a total consequence considering the different weights of these activated rules.

For a better understanding a visual example including two input-variables (flow velocity and water depth) and two activated rules is given in Fig.A.3.4. The exemplary input data to compute the DOF are a flow velocity of 0.75 m/s and a water depth of 0.4 m.

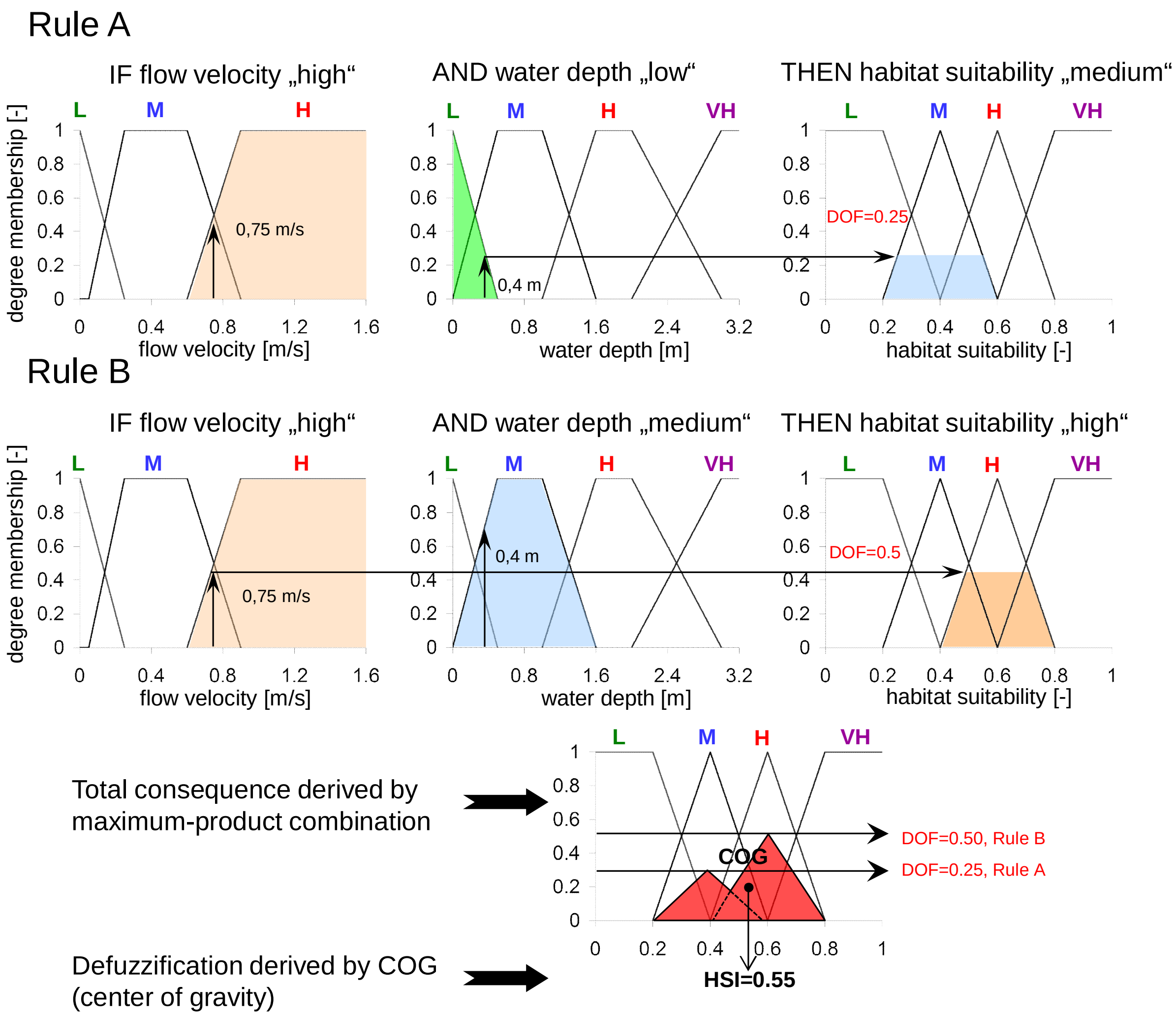


Figure A.3.4: Simplified inference process showing the calculation of DOF (min-max inference) and the aggregation to a total consequence (maximum combination)

For rule A in Fig.A.3.4 the DOF is 0.25 according to the minimum-method applied for ‘high’ flow velocities and ‘low’ water depths. The DOF of rule B is 0.5 as the degree of the membership for ‘high’ flow velocities is less compared to ‘medium’ water depth. As the DOF in rule B is higher than in rule A, it receives a higher weight, visualized in the total consequence of rule A and B. For an ecological interpretation it can be stated that the inference method allows for an automatic weighting of the rules according to the rule-specific DOF. The rule that reflects the best input parameter combination receives the highest weight.

Defuzzification

The global consequence derived by the inference processor is also in a fuzzy form. In order to transform this fuzzy information back into a crisp number, a process named ‘defuzzification’ is applied. In CASiMiR the method ‘Centre of Gravity’ (COG) is implemented. Applying this method gives the result of defuzzification (HSI-value) using the x-coordinate of the COG-value of the total consequence as it is shown in Fig.A.3.4. The entire modelling process is performed for each element in a numerical grid and each time-step leading to maps of spatial distribution and time-series of HSI-values that can be used for further assessments (e.g. WUA, habitat supply, habitat connectivity etc).

PART B: Challenge - Habitat Dynamics

Based on the scientific background - provided in part A - the aim of this part is to present the challenges, bottlenecks and limitations in linking hydromorphological and hyporheic variabilities with corresponding biological requirements in physical habitat modelling. Therefore the three hypotheses formulated in the introduction are elucidated to achieve the overall goal to simulate dynamic HSI-values during the reproduction process of gravel-spawning fish. The content of the first section deals with the question how river dynamic processes can be implemented in physical habitat modelling. In the second part the key questions regarding interstitial habitats are deepened by having a closer look on available indicators and how the indication value can be improved by using a fuzzy-model incorporating interstitial variables. The third part focuses the question how the reproduction of gravel-spawning fish can be addressed in physical habitat modelling.

B.1 River dynamics and habitat modelling

B.1.1 Sediment bottleneck in habitat modelling

Although there is a clear need of integrating morphodynamic processes, as it has been demonstrated in part A, most physical habitat models do not consider changing sediment conditions. The common way of defining riverbed sediments in physical habitat modelling implies a simplification of sediment characteristics to single and static dominant and/or subdominant particle sizes. This assumption may be inadequate in at least three ways:

- it is questionable whether a single dominant particle size is able to describe the habitat requirements of indicator species sufficiently.
- the static consideration of the sediment description in physical habitat models just gives a snapshot in time and does not take into account temporal changes of sediment conditions.
- most physical habitat model consider fixed river beds and hence neglect any river bed movements. Next to changes in the distribution of sediments and subsequent particle size compositions, such bed movements also affect water depths and flow velocities and thus, the simulated HSI-values.

Concerning the reproduction of gravel-spawning fish the sole consideration of a dominant particle size is certainly not sufficient to describe the fish habitat requirements on sediment characteristics. For instance, the simulation of spawning habitat suitability requires several criteria on the sediment characteristics like the maximum particle size a female can move during the process of redd digging (Kondolf, 2000), the permeability of the riverbed including colmation processes and the amount of fine material (Heywood & Walling, 2007). Especially the infiltration of fine sediments into the interstitials of a river bed during the incubation period will not lead to considerable changes in the dominant or subdominant particle size but heavily affects the survival of embryos and larvae (Sear et al., 2008, Chapter A.2.2.5).

A common way to evaluate the changing habitat conditions with varying flow is the calculation of the weighted usable area (WUA, Chapter A.3.2.1). Although most habitat models have interfaces to multidimensional hydrodynamic-numerical models resulting in different hydraulic patterns for different flow rates, it is generally assumed that the spatial sediment distribution remains constant during different flow rates, even though morphodynamic processes are very likely to occur (at least for high flow rates). This aspect becomes even more crucial if the habitat conditions have to be simulated over a certain time period including hydrological variations. In particular suitable spawning habitat conditions for gravel-spawning fish often depend on recent sediment mobilization and mixing processes to provide loosely packed spawning gravels (Merz et al., 2004).

With regard to these criteria it can be stated that the conventional ways of defining the sediment characteristics in physical habitat modelling have limited significance in assessing dynamic habitat qualities in natural rivers - especially for simulating life-stages during the reproduction process the available models fail to meet the required criteria.

B.1.2 Approaches to consider river dynamics in habitat modelling

Recent researches have already started to account for these shortcomings of physical habitat modelling, and several approaches have tried to consider changing substrate characteristics in evaluating fish habitats. Generally these approaches can be subdivided into four categories:

Observational approaches

The first category includes observational approaches that evaluate morphodynamic changes without simulating sediment-transport processes separately but based on measurements or mapping. For instance Wheaton et al. (2010) examined changes in HSI-values of spawning salmonids due to geomorphic river changes using repeated high-detailed topographic surveys. These surveys were used to calculate sediment budgets based on topographical changes of river reaches and to estimate their influence on spawning habitats. Other approaches applied detailed mapping of sediment characteristics. Eastman (2004) and Noack (2005) mapped colmation described by such parameters like pore space and consolidation that are considered as habitat variables in habitat modelling. Although the mapped parameters might be very useful to describe the current river status in a more detailed way, they do not describe the continuously changing sediment characteristics and are always temporal snapshots which do not reflect the dynamic behaviour of rivers. Similarly, the repeated topographical surveys only provide information about changes before and after a certain time period and thereby neglect the processes in-between. However, in order to give a proper assessment of the influence of morphodynamic changes and to make technically feasible predictions of habitat dynamics, information about the temporal and spatial variabilities of morphodynamic processes is required.

‘Pure’ morphodynamic simulations

The second category includes the application of numerical models to simulate morphodynamic processes and to relate their impact on fish habitats without using physical habitat modelling. Hauer et al. (2010), for example, investigated spawning sites using a 2D- morphodynamic model and evaluated the frequency of sediment turnover rates and the renewal of spawning gravels by defining an effective discharge. McDonald et al. (2010) multidimensionally simulated morphodynamics processes to evaluate spawning sites of sturgeon by correlating the location of spawning redds with abiotic parameters gained from the morphodynamic model. These approaches offer valuable information to evaluate fish habitats as they provide detailed information about sediment characteristics and their variations to develop new habitat describing variables. However, there is no interface to a physical habitat model with corresponding physical-biota relationships provided within these approaches. Hence, the interrelations to other important variables which are required for a full description of an abiotic habitat are not considered.

Morphodynamic simulations with conventional habitat modelling

The third category comprises physical habitat models that include or use the output of hydromorphodynamic models but maintain on the standard physical habitat parameters water depth, flow velocity and dominant substrate. Almeida & Rodríguez (2009) coupled a 1D-morphodynamic-numerical model with a mobile bed and multiple particle sizes with PHABSIM. Further examples for combined 2D-morphodynamic-numerical models and habitat model were also presented by Smiarowski (2010) who used the model River2D with its morphological module (R2DM) to simulate the effect of floods on fish habitats or Kerle et al. (2002) who combined morphodynamic, vegetation and habitat models to evaluate long term effects on fish habitats. These modelling approaches pay attention to sediment dynamics and therefore provide more physical information – especially about sediment conditions – compared to standard habitat models as they include bed level changes and their influence on hydraulics and varying dominant particle sizes. However, the implemented habitat modules are still based on a single dominant particle size to describe the sediment characteristic and do not use additional information in terms of multiple particle sizes to define new and more meaningful habitat parameters to describe the habitat of fish.

Morphodynamic simulations using additional sediment variables for habitat modelling

The last category belongs to modelling approaches that combine the advantages of the previous ones by using numerical models to simulate morphodynamics, linking them with habitat modelling tools and applying newly developed habitat variables based on the additionally available information about the abiotic habitat. In this category publications are rare although the need of this modelling type can be found in numerous publications (e.g. Pitlick & Wilcock, 2001; Maddock, 1999; Kondolf, 2000; Hauer et al., 2007; Wieprecht , 2009; Vaughan & Ormerod, 2010). Examples concerning this category may be provided by Hauer et al. (2007) and Escobar-Arias & Pasternack (2010). They used simulated bottom shear stresses of their hydrodynamic-numeric models to derive morphodynamic processes like erosion and sedimentation or the initial transport of particle sizes with corresponding consideration in habitat modelling. Nevertheless the simplification of morphodynamic processes to bottom shear stresses does not reflect complex sediment dynamics sufficiently. Moreover bed level changes and their influence on hydraulics are neglected.

Based on this brief review of available tools concerning sediment dynamics in physical habitat modelling it can be stated that there is still a lack of properly implementing morphodynamic processes in physical habitat modelling approaches. The proposed modelling approach for the reproduction period of gravel-spawning fish presented in this thesis clearly belongs to the last category, as numerical tools are used to gain information about the abiotic characteristics and new habitat variables are derived to be applied dynamically in a habitat simulation tool. This leads to the first hypothesis which is specified in the following section.

B.1.3 Hypothesis 1 – Hydromorphological variability and physical habitat modelling

The first hypothesis is that a 3D-numerical model is able to simulate the relevant fluvial dynamic processes influencing the sediment characteristics of gravel river beds. This includes the simulation of the temporal and spatial variability of abiotic hydromorphological habitat variables to describe the habitats for the life-stags during the reproduction period. The exact requirements for a numerical model tool arise on the one hand from the static sediment bottleneck in existing habitat modelling approaches and on the other hand from capabilities to derive new habitat variables describing the dynamically changing abiotic environment during the reproduction period.

Regarding the static sediment bottleneck a numerical model has to be capable to simulate the temporal and spatial variability of all relevant hydromorphological variables affecting the reproduction of gravel-spawning fish. These are mainly

- water depth and flow velocity distributions,
- distributions of bed- and suspended loads,
- varying particle size compositions,
- horizontal and vertical sorting,
- as well as erosion and sedimentation.

To derive new habitat variables that are not direct outputs of the numerical model, the simulation results have to be provided in appropriate formats to assure further calculations. This implies, for example, the calculation of the amount of accumulated fine sediments or the permeability in the riverbed that are both important habitat variables for simulating habitat quality during the incubation period.

In addition the dimensionality of the numerical model plays an important role. 1D- models are not applicable due to their simplification in depth- and width-averaging values which does not meet the required spatial distribution of habitat variables. 2D-models allow for better predictions of hydromorphological values but provide still depth-averaged values to simulate sediment-transport processes that occur near the river bed. This might not be sufficient for the modelling purposes in this thesis as the infiltration and accumulation of fine sediments in the interstitials of the riverbed strongly depend on an accurate simulation of near-bed processes. Particularly in heterogeneous rivers, 3D-phenomena (e.g. secondary flows) can largely influence the magnitudes and directions of sediment transport processes and thus the infiltration processes. Therefore a correct simulation of all river bed forces using a 3-dimensional numerical tool is indispensable to evaluate sediment dynamics for reproduction of gravel-spawning fish.

B.2 Interstitial indicators and habitat modelling

One key task in this thesis is to define the dynamically changing quality of interstitial habitats during reproduction of gravel-spawning fish. This requires suitable indicators describing the quality of interstitial habitats in its temporal and spatial variability. On the one hand the indication value of habitat variables depends on how exactly the abiotic conditions of habitat requirements during the incubation period can be described. On the other hand the indication value depends on the feasibility to be implemented into a modelling approach to predict temporal and spatial variations of interstitial habitat quality. In scientific literature the main interstitial habitat indicators are analyses of particle size distributions, colmation degrees and infiltration masses of fine sediments into the gravel-framework of river beds which are elucidated in the next sections.

B.2.1 Particle size analyses and interstitial habitat

The influence of the particle size distribution on spawning and incubation habitats in the interstitial of riverbeds have been early recognized (Cordonne & Kelley, 1961; Chapman, 1988) and numerous approaches and parameters have been developed to evaluate different analyses of the particle size distribution by linking them to streambed habitat suitability or survival rates during the incubation stage of gravel-spawning fish (Haschenburger & Roest, 2009; Dirksmeyer & Brunotte 2009).

B.2.1.1 Indicators derived from particle size analysis

Bunte & Abt (2001) provide a detailed overview about standard analyses of particle size distributions ranging from mean values like the characteristic particle size and the geometric mean to the skewness and kurtosis or the sorting coefficient of particle size distributions. Other substrate indices were developed by Lotspeich & Everest (1981) who introduced the Fredle-Index as quotient of the geometric particle size and sorting coefficient. Tab.B.2.1 provides an overview of the most frequently used particle size indices in evaluating sediment characteristics for interstitial habitats.

Table B.2.1: Sediment indices to evaluate substrate characteristics for reproduction habitats

variable	expression/formula		meaning
percentage of fines	<63mm <2mm <1mm		definition of constant thresholds (e.g. 15% less than 2mm give 50% survival, Kondolf (2000))
geometric mean diameter	$d_g = \sqrt{\mathrm{d}_{84} \cdot \mathrm{d}_{16}}$	(Eq.B.2.1)	d_g=geometric mean grain size
sorting-coefficient (SO)	$SO = \sqrt{\frac{d_{84}}{d_{16}}}$	(Eq.B.2.2)	the higher SO the less pore space is available and vice versa
Fredle-Index (FI)	$FI = \frac{d_g}{SO}$	(Eq.B.2.3)	the higher FI the higher pore space is available and vice versa

Less common but with increasing awareness are analyses of particle size distributions to calculate permeability and several studies compared permeability values with reproduction successes (e.g. Chapman, 1988; Roche, 1994; McBain & Trush, 2001). The permeability mainly depends on the particle size distribution, degree of packing (porosity) and viscosity of water. Accordingly, scientific literature provides several empirical formulas to calculate both porosity (e.g. Carling & Reader, 1982; Wu & Wang, 2006; Wooster, 2008; Frings, 2011) and permeability (e.g. Hazen, 1892; Carman, 1956; Terzaghi 1964) based on particle size distributions.

It is important to note that the permeability in this thesis is used as a substitute for the hydraulic conductivity as in ecological and biological literature the term permeability is commonly used to describe the hydraulic conductivity. From a physical point of view this is not fully correct, as the permeability [SI-unit: m²] describes a measure of how well a porous gravel-framework transmits a fluid without concerning the fluid itself, while the hydraulic conductivity [SI-unit: m/s] additionally considers fluid attributes like viscosity.

B.2.1.2 Indication value of particle size analyses

The definition of critical thresholds of percentages of fine sediments less than 1 mm to 6 mm are probably the most frequently used indication parameter and the literature provides a wide range of different thresholds for different sizes of fine sediments. This approach is mostly criticized because only a part of the whole particle size distribution is considered (Tappel & Bjornn, 1983). Moreover, many studies exclude large particle sizes from the analysis. This artificially increases the amount of fine fractions (Kondolf & Wolman, 1993). Young (1991) examined all of the above mentioned analyses in a laboratory study and found out that indices which consider the particle size distribution as a whole are more suited for evaluating differences of survival rates (Dirksmeyer, 2008).

In terms of permeability McBain & Trush (2001) stated that this variable defines the variability of interstitial habitat in a more appropriate way than common particle size analyses which consequently brings a higher indication value. Although strong correlations between permeability and survival rates of gravel-spawning fish were observed (e.g. Lotspeich & Everest, 1983; Tappel & Bjornn, 1983) the suitability as an indicator might be problematic as natural river sediments not only show a wide range of magnitudes of permeability but also a highly spatial variability, primarily in the vertical direction (Peterson & Quinn, 1996).

Analysis of particle size distributions generally provide valuable information about sediment characteristics and can easily be calculated using sediment samples or simulated particle size distributions with numerical modelling tools. Nevertheless, it remains questionable whether these sediment indices allow for a sufficient description of the abiotic conditions in interstitial habitats. According to Dirksmeyer & Brunotte (2009) there is no single or dominant sediment index including all relevant functions of a particle size distribution to the reproduction period of gravel-spawning fish species. Although combinations of different indices might be a solution the influence of complex morphodynamic processes like colmation and hyporheic exchange processes such as down- and upwelling cannot be described by using only information gained from particle size analyses. Moreover, the purely sedimentary description lacks important biological or chemical variables that are important for interstitial habitats.

B.2.2 Colmation and interstitial habitat

Although nowadays assessments of colmation are commonly used as indicators for interstitial habitats in river management, no standard method for quantifying colmation is available (Sennatt et al., 2006). Many of the available methods for assessing colmation focus on the surface layer of river beds and only in recent research, techniques have been used to assess colmation in subsurface zones. The next section provides a brief overview of available methods for estimating the degree of colmation.

B.2.2.1 Existing approaches to assess colmation

Next to the differentiation between surface and subsurface techniques, assessment methods can be further categorized in visual observations (mapping) and direct measurement techniques.

Visual Observations

Mapping methods of colmation or embeddedness were firstly proposed by Platts et al. (1983) who estimated embeddedness in five classes ranging from 0 % to 100 %. The EPA EMAP method (Peck et al., 2000) assesses embeddedness in eleven cross-sections with a distance of four times the river width by estimating the percentage of fines resulting in embeddedness levels ranging from low to high. Another proposed method is the USGS method (Fitzpatrick et al., 1998) which visually estimates the average height (in percent) of buried particles to the average height of the fine sediment layer resulting in percentages of embeddedness. The most promising method was developed by Schaelchli (2002) and adapted by Eastman (2004). It includes the mapping of dominant and subdominant particle sizes grouped in 9 classes from <0.063 mm to > 200 mm and additionally consider the assessment of the degree of colmation, consolidation and pore space in 5 classes.

Visual observation are repeatedly criticized for being subjective as these methods depend on the sensitivity and training of the observer and several studies have shown that comparisons of different mapping methods lead to different results (Sennatt et al., 2006, Potyondi & Sylte, 2008). Furthermore, it is difficult to conduct visual observations in turbulent waters or in waters with a high turbidity. Nevertheless, a proper visual observation method might allow for an evaluation of not only physical colmation processes but also about the biological/chemical effects on colmation.

Direct Measurements

A simple measuring method for surface colmation or embeddedness is to measure the depth to the embedded layer and the exposed particle height (proposed by Burns & Edwards, 1985). Another one is the method of Finstad et al., (2007) which was developed to assess the interstitial space for juvenile fish by measuring the length of a tube that can be stuck into the pores of the surface riverbed. Another measurement technique, especially for subsurface colmation is freeze-coring, although it does not measure “real” colmation but provide detailed information about the percentage of fine sediments in different sediment layers (Stocker & Williams, 1972). Additional techniques are measurements of permeability which record the water volume through the interstices (Dahm & Vallet, 1996), the detection of changed wood colour with hypoxia through inserted wooden stakes (Marmonier et al., 2004) or a penetrometer that measures the mechanical resistance when manually driving a rod into the sediments (Maquaire et al., 2002). A comparison of different assessment methods conducted by Descloux et al. (2010) yields a strong relationship between the percentage of fines obtained by freeze-coring and the measurements of permeability that might allow a relation to clogged sediments. Penetrometry and wooden stakes yielded poor results for assessing subsurface colmation.

Some direct measurement techniques like freeze-coring or the measurement of permeability are proper methods to assess physical and mechanical colmation. But the considerable effort required for taking freeze-core samples and the following sieving analyses limits the applicbility of this method, particularly in terms of the high spatial and temporal variability of colmation. Descloux et al. (2010) suggests the use of permeability as a surrogate for colmation in monitoring programs because it is a relatively fast and simple measurement technique and represents progressive colmation in form of reduced permeability. However, the biological and chemical aspects are not considered within these measuring techniques.

B.2.2.2 Indication value of colmation

Compared to analyses of particle size distribution the assessment of colmation provides more information as it considers not only sedimentological parameters but also integrates other environmental influences like biological or chemical aspects (Chapter A.2.1.4). Hence, a very high indication value for colmation can be assumed. But the colmation as an integrating parameter has one significant disadvantage: it is not predictable. All assessment techniques solely represent the current state of colmation in a river – a snapshot in time – and neglect the dynamic processes behind the evolution of colmated river beds. This limits the applicability as an indicator for interstitial habitats as no link to numerical modelling tools is possible which is required to achieve predictability. The only way of implementing a colmation assessment method is to use the analyses of freeze-core samples in terms of permeability. However, identically to particle size analyses, this neglects both biological and chemical aspects and only describes the physical colmation. Furthermore, there is no standard definition of colmation existing in scientific literature (see Chapter A.2.1.4). This may lead to difficulties concerning the interpretation of different colmation levels.

B.2.3 Sediment infiltration and interstitial habitat

To delineate sediment infiltration and accumulation processes from colmation it can be stated that colmation is an integrated value which encompasses mechanical, biological and chemical processes while sediment infiltration and accumulation in the river bed describes just the sedimentological colmation (see also Chapter A.2.1.4). The infiltration and accumulation of fine sediments in the riverbed interstitials is a dynamic process which is well known to affect the incubation habitat and have been in focus of many studies (see Chapter A.2.3.2). The intruding fine material has a significant influence on the resulting particle size distribution due to the increasing amount of fine material that reduces the permeability. The measurement techniques of sediment infiltration are not described here. They are described in Sear et al. (2008). As the predictability of sediment infiltration processes is an important requirement for the proposed modelling concept, three different concepts of existing modelling approaches are briefly introduced in the following section.

B.2.3.1 Existing approaches to simulate sediment infiltration

The available simulation approaches for sediment infiltration can be distinguished between simple empiric formulas (Lisle & Lewis 1992), semi-empirical simulation approaches (Schaelchli, 1993) and numerical methods (Alonso, 1992; Cui et al., 2008).

Empirical simulation approach (Lisle & Lewis, 1992)

Lisle & Lewis (1992) measured bed load rates of particle sizes between 0.25 mm and 4.0 mm at different discharges in three rivers to derive an empirical power function for a calculation of mean bed load rate (Eq.B.2.4). Accumulated fine material was measured in cans buried in the river bed and related to fine bed load rates via another power function to simulate the amount of infiltrated sediments (Eq.B.2.5).

fine bed load rates: $$q_b = (2.5 \cdot 10^{-5}) \cdot Q^{2.72} \qquad \text{Eq.B.2.4}$$

sediment infiltration: $$m_k = 2.03 \cdot {q_{b,T}}^{0.412} \qquad \text{Eq.B.2.5}$$

Based on the infiltrated material m_k, Lisle & Lewis (1992) calculated the change of permeability. This substantially simplified empirical model is only based on measurements of three rivers with similar bed material which subsequently limits the applicability to other river types. Moreover, the approach is only based on bed load rates and neglects the gravel-matrix of the river bed which is a major factor for sediment infiltration processes (Sear at al. 2008).

Semi-empirical simulation approach (Schaelchli, 1993)

The infiltration and clogging model of Schaelchli (1993) is based on the classical equation for cake filtration to calculate the integrated seepage volume V_S through a certain filter area A_F considering two kinds of infiltration resistance: The first infiltration resistance β of the clean unsaturated river bed and the second infiltration resistance α considering the growing infiltration resistance due to the deposited fine sediments in the interstitial (Tab.B.2.2).

Table B.2.2: Set of equations to calculate sediment infiltration using the semi-empirical approach of Schaelchli (1993)

seepage volume:		$\frac{dV_S}{dt} = \frac{A_F \Delta p_S}{\mu(\alpha+\beta)}$	Eq.B.2.6
infiltration resistance:	resistance due to deposition of fines	$\alpha = \frac{r_S c_S V_S}{A_F}$	Eq.B.2.7
	specific resistance	$r_S = \frac{e_S \cdot \theta^{0.5}}{\left(\frac{d_{10}}{d_m}\right)^{3.5} \cdot Re_*^{1.5} \cdot i^{0.67}}$	Eq.B.2.8
	resistance of clean gravel-framework	$\beta = \frac{L_S \cdot g}{k_o \cdot \nu}$	Eq.B.2.9
	maximum	$\gamma_{max} = \frac{c_R \left(\frac{d_{10}}{d_m}\right)^{1.25} Re_* \cdot i^{2.5} \left(\frac{c_S}{\rho_W}\right)^{0.75}}{\theta}$	Eq.B.2.10
infiltration mass:		$\frac{dm_k}{dt} = c_S \cdot \frac{dV_S}{dt}$	Eq.B.2.11
permeability		$k_P = \frac{dV_S}{dt} \cdot \frac{1}{A_F} \cdot \frac{1}{i}$	Eq.B.2.12
permeability (minimum)		$k_{Pmin} = \frac{h_S g}{\gamma_{max} \nu} \cdot$	Eq.B.2.13

The total infiltration resistance (γ) is the sum of α and β and the empiric variable e_S is used to calculate the specific infiltration resistance (r_s). Based on a multiple regression analysis of the laboratory investigations performed by Schaelchli (1993), the variable e_S is assumed to range between $1.2 \cdot 10^{11}$ - $1.2 \cdot 10^{12}$. The permeability (k_p) is calculated on the basis of temporal variation of the seepage volume (V_S) and on the basis of the hydraulic gradient (i) using Darcy's law. Furthermore Schaelchli (1993) defined equations to calculate the limiting state of sediment infiltration which is the equilibrium between deposition and resuspension. Therefore he developed Eq.B.2.10 to compute the maximum infiltration resistance (γ_{max}) with an empirical factor c_R of 3.3×10^{11}. Accordingly, a minimum permeability (k_{pmin}) can be computed by Eq.B.2.13.

Schaelchli identified five variables having a significant influence on clogging processes:

- the near bed suspended sediment concentration that deliver fine sediments to the river bed (c_S)
- the particle size distribution of the riverbed material (d_{10}/d_m)
- the solid Reynolds number (Re*)
- the dimensionless shear stress (θ)
- the hydraulic gradient (i)

Schaelchli's equations allow for a dynamic calculation of infiltration processes which makes it highly valuable for simulating changing interstitial habitat conditions over time. However, for practical applications it might be difficult to get information about the temporal and spatial heterogeneity of required input variables like the vertical hydraulic gradient (i) or the seepage length (L_S).

Numerical simulation approach (Cui et al., 2008):

The sediment infiltration model of Cui et al. (2008) simulates the infiltration process on the basis of the sediment continuity equation in vertical direction considering a trapping coefficient which accounts for particles to be trapped during the infiltration process at different sediment depths (Eq.B.2.14).

$$\frac{1}{q_S}\frac{\partial q_S}{\partial z} = -\beta_0 \cdot exp\left(\Phi_c \frac{F_{mk}/F_{Sat}}{1 - F_{mk}/F_{Sat}} \right) \qquad \text{Eq.B.2.14}$$

In Eq.B.2.14, the trapping coefficient (β_0) describes the resistance for the sediment infiltration into a clean gravel-framework void of fine sediments while Φ is a dimensionless calibration factor. Eq.B.2.14 can be solved numerically with given values of β_0 and Φ. There is, no approach to calculate the influence of sediment infiltration on permeability provided by Cui et al. (2008). However, porosity is included in the trapping coefficient using a proportional ratio of water flowing through the river bed to the interstitial flow velocity. The approach of Cui et al. (2008) considers the infiltration process in the riverbed itself but do not provide information regarding the amounts of fine sediments that are delivered to the riverbed and the amounts that stay in suspension. This requires the linkage to a numerical sediment-transport model. However, most numerical sediment-transport models do not support a spatial discretization of the riverbed in vertical direction but work with virtual multiple sediment layers. Furthermore the estimation of β_0 and Φ for a given particle size composition might be difficult.

Numerical simulation approach (SIDO, Alonso, 1992):

SIDO (Sediment Intrusion and Dissolved Oxygen) simulates the sediment transport in one dimension using a daily time-step and links these results to a vertical 2D-model that simulates the sediment infiltration into salmonid redds. The infiltration starts from the bottom upwards as an unimpeded infiltration through the gravels is assumed. Next to sediment infiltration SIDO simulates the intragravel flow rates, oxygen consumption by embryos, temperature based egg-development and intragravel DO-concentrations. The 1D-approach to represent flow and sediment transport may not be able to simulate the required spatial resolution of fine sediment delivery to the riverbed. Furthermore the infiltration module in SIDO does not consider any infiltration resistance and the gradually filling from the bottom were refuted by several studies (e.g. Schaelchli, 1992; Wu, 2000; Cui et al., 2008). According to Sear et al. (2008), SIDO is highly sensitive to the portion of particles less than 10 mm given the limited range of particle sizes the model can accommodate with which results in a strong dependency on the calibration process.

B.2.3.2 Indication value of sediment infiltration

Sediment infiltration and accumulation lead to a reduction of available pore space, permeability and surface-groundwater interactions. The resulting reduction of permeability obtained by the sediment infiltration models must be clearly distinguished from the permeability gained from pure particle size analyses as the influence of sediment infiltration mechanisms like the increasing infiltration resistance over time is not considered. Given the available modelling approaches the requirements on predictability are fulfilled. Furthermore the linking of these modelling approaches to numerical modelling tools meets the requirements on spatial and temporal resolution. But sediment infiltration is a purely sedimentary process, similarly to the particle size analyses, and does not include any biological or chemical processes that might be important for interstitial habitats.

B.2.4 Comparison of available indicators for interstitial habitats

In order to evaluate the indication values of the three presented indicators, they are contrasted with the abiotic habitat requirements during the reproduction period of gravel-spawning fish (Tab.B.2.3). The habitat requirements are summarized into four key habitat variables (according to Chapter A.2.2.5): morphological variability, availability of dissolved oxygen, hyporheic exchange and water temperature. Additionally, the indication criteria formulated in Chapter A.2.2.4 are considered.

Table B.2.3: Comparison of interstitial indicators with key habitat variables during incubation period and general indication criteria

key factors during incubation period			
	sediment indices	colmation	sediment infiltration
morphological variability	++	+/-	++
dissolved oxygen	--	+	-
hyporheic exchange	+/-	+	+
interstitial temperature	--	--	--
indication criteria			
conceptual relevance	--	+	-
practical aspects	+	+	+
interpretability	++	+/-	+
response variability	-	-	-
predictability	++	--	++

While sediment indices and sediment infiltration can be linked to numerical modelling tools, these indicators are able to represent the spatial and temporal morphological variability adequately whereas colmation as a measured or mapped parameter only provides information about spatial heterogeneity of the current status (temporal snapshot). In terms of dissolved oxygen colmation gets the highest rank as it considers integratively sedimentological, biological and chemical clogging processes and can be qualitatively related to the availability of dissolved oxygen concentrations. The indicator sediment infiltration is slightly higher ranked than the indicator of sediment indices because sediment infiltration considers the resistance of gravel-structures of the river bed and the resistance of increasing infiltrating fine sediments. Thereby sediment infiltration allows for a more detailed calculation of permeability. Similarly the indication value for hyporheic exchange processes can be evaluated by using the permeability gained from particle size analyses or sediment infiltration. Regarding the habitat variable water temperature which defines the metabolic activity and egg development none of the parameters is suitable.

In terms of general indication criteria like the conceptual relevance colmation is advantageous compared to the other interstitial parameters, mostly due to its integrative nature. All indicators can easily be measured and analysed in the field or laboratories to ensure reproducibility and practicability. Sediment indices and sediment infiltrations can easily be interpreted given to existing equations, while the interpretability of colmation might be difficult due to its qualitative nature and the different available definitions in literature. The response variability which describes the possibility to identify certain stressors to changing habitat conditions is a very difficult criterion to meet for interstitial indicators as the survival of gravel-spawning fish depends on complex interactions among physical, biological and chemical variables. None of the presented indicators have the ability to fulfil this criterion for the entire spectrum of possible impacts. In terms of predictability both sediment indices and sediment infiltration are highly ranked while the assessment of colmation gets a poor ranking due to its qualitative and static nature.

Based on the evaluation of the indication values it can be stated that none of the investigated variables and processes is able to fulfil all criteria sufficiently. Subsequently, more appropriate indicators are required to describe the interstitial habitat quality during reproduction. This leads to the second hypothesis elucidated in the next section.

B.2.5 Hypothesis 2: Interstitial Habitat Suitability (IHS) and hyporheic variability

Hypothesis 2 includes the fuzzy-simulation of an interstitial habitat suitability (IHS) as an indicator for the hyporheic variability during the reproduction period of gravel-spawning fish. Instead of describing the colmation and clogging process in detail, the idea of the fuzzy-model is to contrast the hyporheic variability with requirements of gravel-spawning fish during reproduction. The hypothesis includes the following main aspects:

- a combination of habitat variables describing the interstitial habitat conditions provide a higher indication value compared to single indices and processes.
- the interstitial habitat during incubation period cannot be described using only sedimentological variables.
- the availability of dissolved oxygen in the interstitial is a key variable describing the reproduction success.
- the IHS-values have to be calculated by using simulation tools to ensure predictability and to allow prognoses over time.

The first two aspects aim at the insufficient description of interstitial habitats using single indices or parameters as the interstitial habitat is influenced by multiple factors from different disciplines. This includes variables describing the hyporheic exchange and biogeochemical processes as well as water temperature. This insufficient description of sedimentological parameters is also in coincidence with the findings of Dirksmeyer (2008) who did not find any reliable correlation between survival rates of salmonids and purely sediment based parameters. The third aspect is based on several studies which found a clear relationship between survival rates and availability of dissolved oxygen (Chapman, 1988; Ingendahl, 2001; Greig et al., 2007). Thus, dissolved oxygen can be considered as a master variable for reproduction success.

According to Chapter A.2.5 the oxygen availability is predominantly defined by the sediment characteristics, the interstitial temperature and the biogeochemical processes. It is therefore hypothesized that linking these abiotic variables via a fuzzy-logical approach improves significantly the indication value of the hyporheic variability compared to existing indicators. In particular, the predictability of the key interstitial habitat variables, their dynamic consideration, the interpretability of the fuzzy-model, and the conceptual relevance to certain stressors may lead to a high indication value of the interstitial habitat suitability. Additionally - given the high uncertainty due to the high spatial and temporal variability of these factors and processes - the fuzzy-logic approach seems to be an appropriate method to estimate the interstitial habitat suitability as an indicator for hyporheic variability.

B.3 Reproduction and habitat modelling

B.3.1 Consideration of reproduction as ecological indicator

The high ecological significance of reproduction habitats as a basic element for the development of stable populations is explicitly included in the concept of ecological functions and services (Chapter A.2.2.2). According to Schiemer et al. (2003) the early-life stages are extra-significant because the highest mortality occurs in these stages due to starvation, predation but also due to physical habitat quality and availability that are defined by temperature limits, mechanical shocks, oxygen supply and dispersal during all development stages (Elliot, 1994). Based on these statements Kamler (1992) concluded that the success or failure of fish populations is strongly determined during the reproduction period. As age structures and fluctuations of fish populations provide a robust indication of the fluvial ecological status the reproduction represents one critical component in evaluating river ecology. Given these factors, one of the key objectives explicitly formulated in the WFD is the restoration of reproductive grounds for indicator fish species (Hauer, 2007) in order to achieve the overall goal - a good ecological status in rivers.

B.3.2 Approaches to simulate reproduction of salmonids

Success or failure of reproduction processes have been investigated mainly in fisheries research and are published as empirical functions or as components of individual-based and population models. Physical habitat models have been widely applied to simulate spawning habitat conditions (e.g. Moir et al. 2005, Hauer et al. 2007, Schneider et al. 2007, Gard 2009) or to verify the effectiveness of mitigation measures to provide sufficient spawning grounds (e.g. Merz et al. 2004, Wieprecht et al. 2006, Mouton et al. 2008, Wheaton et al. 2010). Despite the importance of natural reproduction, the simulation of reproduction habitats has been hardly considered in physical habitat modelling. Moreover, Lisle & Lewis (1992) stated that the key to embryo survival is not the condition of spawning gravel before or immediately after spawning but during the month of incubation. The next two sections provide information about empirical physical simulation approaches and habitat-based population models to simulate reproduction of gravel-spawning fish.

B.3.2.1 Physical-based empirical simulation approaches

Most empirical simulation approaches are based on regression models using data of field investigations. They differ in number (single versus multi-parameter approaches) and choice of involved parameters and result mostly in an egg-to-fry-survival rate given in percent. In Tab.B.3.1 different approaches are listed to provide examples of empirical approaches to simulate reproduction.

Table B.3.1: Examples for empirical simulation approaches for egg-to-fry survival rates

habitat variable	egg-to-fry survival (ETF) [%]		species	literature
interstitial velocity [v_{int}]	$ETF = 167.0 + 46.3log(v_{int})$	Eq.B.3.1	Sockey salmon	Cooper (1965)
fraction < 0.85 mm [p_1] fraction < 9.50 mm [p_2]	$ETF = 94.7 - 0.1p_1p_2 + p_2^2$	Eq.B.3.2	Steelhead	Tappel & Bjornn (1983)
fraction < 0.06 mm [p_1] fraction < 2.00 mm [p_2]	$ETF = 83 - 2.3(p_2) - 6(p_2 \cdot p_1)$	Eq.B.3.3	Atlantic salmon	LaPointe et al. (2004)
permeability [k_p, cm/h]	$ETF = 0.1488 \cdot ln(k_p) - 0.8253$	Eq.B.3.4	Atlantic salmon, Brown Trout	Tagart (1976) McCuddin (1977)

Tab.B.3.1 only gives a short extraction of available empirical function. Although the results are provided in form of exact survival rates, it can be stated that these empirical relationships are rather rough estimators than precise predictors of ETF-survivals. Lisle and Lewis (1992) compared the approaches of Cooper (1965) and Tappel & Bjornn (1983) resulting in discrepancies of more than 100 %. McBain & Smith (2001) found the confidence intervals (95 %) for survival rates ranging from 9 % – 93 % when applying the approach of Tappel & Bjornn (1983), while there was 18 % - 49 % when applying the approach of Tagart (1976) and McCuddin (1977). Such large discrepancies are not surprising because there are various and dynamically varying environmental conditions during reproduction, which are altogether neglected in the empirical simulation approaches. Moreover, the approaches consider only one sedimentological parameter and neglect other important habitat variables like the exchange between surface water and groundwater and biological activities which influence the available oxygen during the development stages (see also Chapter A.2.2.5). There are also numerous empirical (exponential, power, hyperbolic) functions using the variable temperature to calculate an ETF-survival (Elliott & Hurley 1998). These kind of empirical functions are mostly applied in habitat-related population models which are described in the next section.

B.3.3.2 Reproduction in habitat-related IBMs and population models

Physical habitat-based population models basically relate fish mortality to spatial and temporal habitat limitations starting with spawning and egg deposition which subsequently grow from one life stage to another (Bartholow, 1996). One habitat related individual-based population model for trouts is InSTREAM developed by Railsback et al. (2009). It considers reproduction divided in three stages: spawning, incubation and emergence. While spawning is simulated using a multiplicative combination of the three traditional habitat parameter water depth, flow velocity and substrate, the egg-to-fry survival is determined by four mortality risks: low/high temperature, scouring during high flows, dewatering and superimposition. Emergence is used to transfer the 'egg' or 'larval stage' to a 'new fish' without considering any additional mortality. A daily time-step is included updating three varying input-variables: temperature, flow and turbidity as well as the number of survived eggs/fish based on the mortality risks. The role of physical habitat modelling is primarily to get the spatial and temporal distribution of cell units that trouts may occupy and to gain information about hydraulic parameters and spawning gravel availability. The model procedure starts with the number of viable eggs which depends on fish fecundity and the number of successfully fertilized eggs. Each mortality risk during reproduction is executed separately using numerous empiric and probabilistic functions affecting the number of survived eggs.

Other examples of habitat-based population models considering reproduction are SALMOD (Bartholow et al., 1993) and MODYPOP (Capra et al., 2003) which can be allocated to the same model type. Both models use implemented empiric and probabilistic functions and the weighted usable areas (WUA) to describe habitat conditions during reproduction. These habitat-based population models not only incorporate several life-stages during reproduction but also unsteady flow data. This represents a step forward in a biological way of thinking because parameters like fecundity, fertilization, and egg predation are incorporated in the model systems. But from a physical point of view the abiotic environment during reproduction is still based on the conventional habitat variables whereby the temperature is included as an additional variable. Especially, the simple description of sediment characteristics presents a limitation within these models. Moreover, morphodynamic processes like changes of sediment permeability due to infiltration as well as biogeochemical processes affecting the survival of eggs and larvae are still neglected. But it is noteworthy that the aim of these kinds of models is the simulation of population dynamics for time periods of several years to get information about the size and age structure of populations (Railsback et al., 2009) without focusing on reproduction in detail.

B.3.3 Hypothesis 3: Physical habitat simulation and aggregation to Reproduction Habitat Suitability (RHS)

As the reproduction process of gravel-spawning fish is highly dependent on varying environmental conditions during spawning, incubation and emergence (e.g. Kondolf, 2000) it is hypothesized that a multi-step fuzzy-logic habitat modelling framework simulating the time-dependent habitat suitability for the entire reproduction period allows an assessment of the reproduction habitat suitability (RHS) of river reaches (hypothesis 3). On the one hand, the model framework is based on simulating the temporal and spatial variations of all relevant hydraulic and morphodynamic processes using a detailed numerical modelling tool (hypothesis 1). On the other hand it is based on the interstitial habitat suitability (hypothesis 2) giving information about the hyporheic variability throughout the entire incubation time. The reproduction habitat suitability (RHS), as the final output of the multi-step habitat modelling framework, is the result of linking the habitat suitability indices of each life-stage during reproduction. However, the RHS aims not to provide information regarding survival rates but to provide information regarding the effects of hydromorphological and hyporheic variability on the habitat quality for reproduction. The concept and development of each component of the fuzzy-logical modelling framework is elucidated in Part C.

PART C: Model Concept

This part of the thesis describes the concept of the multi-step fuzzy-logic habitat modelling framework to simulate the reproduction habitat suitability (RHS) of gravel-spawning fish. Firstly, an introduction of the modelling framework is provided containing an overview of all modelling steps. Then each model component is presented with detailed explanations of the model procedure. In the last section the modelling framework is expounded including its applicability and limitations.

C.1 Modelling framework for reproduction habitats

C.1.1 Introduction to the modelling framework

The proposed multi-step habitat modelling framework is based on the principles of physical habitat modelling which describe the abiotic environment using habitat variables and link them to biotic responses of indicator species using physical-biota relationships. To allow estimations of the reproduction habitat suitability both abiotic and biotic expertise is required. Therefore the abiotic habitat variables are simulated using numerical and empiric modelling tools which are further used in a multivariate fuzzy-approach linking them to habitat suitability indices. All fuzzy-sets and fuzzy-rules developed within the modelling framework are based on literature and on the experience of biologists to assure the application of highest available expertise-knowledge for the proper estimation of composite effects of applied habitat variables. Fig.C.1.1 gives an overview of the modelling framework.

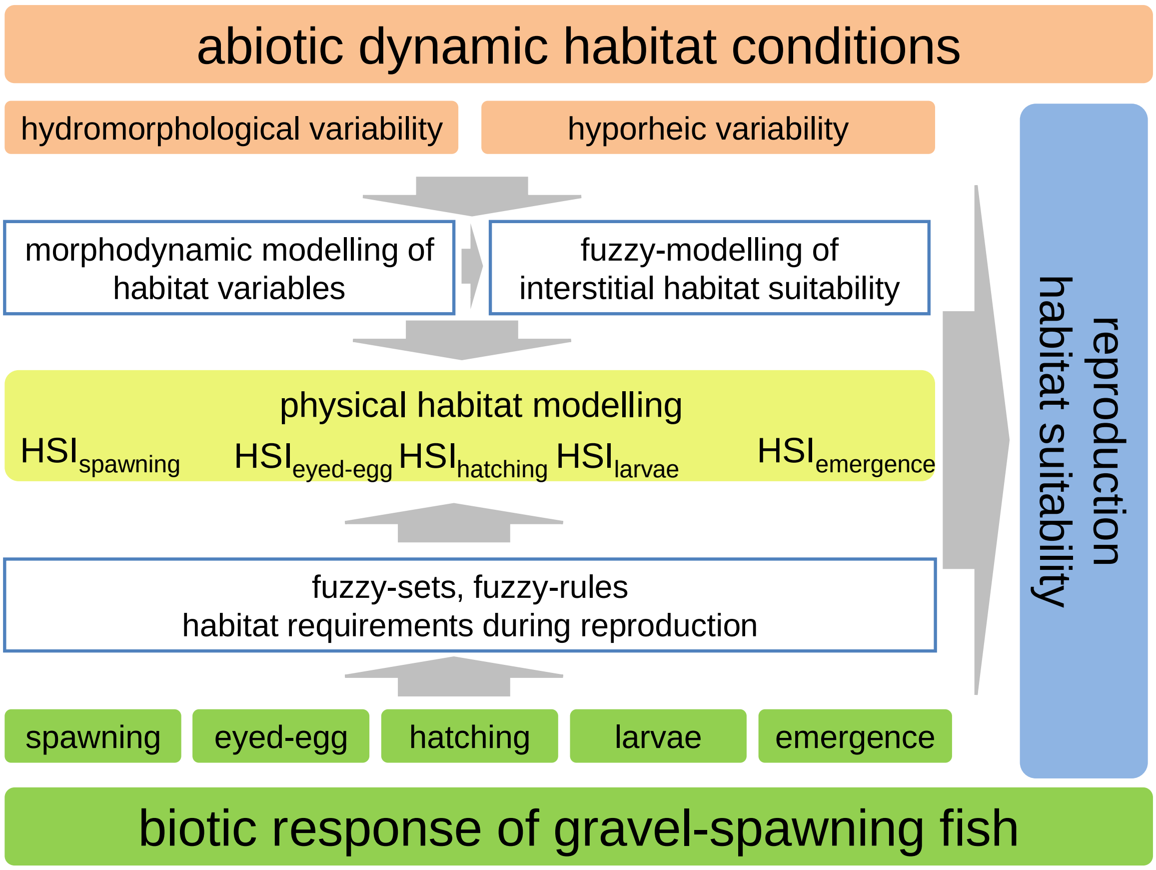


Figure C.1.1: Proposed physical habitat modelling framework to simulate the reproduction habitat suitability (RHS) of gravel-spawning fish

The framework presented in Fig.C.1.1 is structured into four major parts. As the dynamic nature of changing abiotic habitat variables is a major concern of this framework, the hydromorphological variability is simulated using multidimensional numerical tools (Chapter C.1.2). To account for the hyporheic variability these numerical results are further used to derive additional interstitial habitat variables for a fuzzy-model simulating the interstitial habitat suitability (IHS, Chapter C.1.3). In a third step, the habitat requirements for each life-stage during reproduction (spawning – eyed-eggs – hatching – larvae – emergence) are defined separately. Fuzzy-sets of the chosen habitat variables are specified for each life-stage and are linked to a life-stage-specific habitat suitability index through corresponding fuzzy-rules (Chapter C.1.4). The last part integrates the intermediate results of each life-stage sub-model of physical habitat modelling (HSI-values) to an aggregated reproduction habitat suitability (RHS) of a river reach (Chapter C.1.5). Using this modelling procedure the biotic response to the abiotic variability of river conditions in form of dynamic HSI-values and corresponding RHS-values provides valuable information about the potential availability and quality of reproduction habitats.

This framework extends the applicability of physical habitat modelling via the explicit consideration of hydromorphological and hyporheic variability what allows a dynamic and thus a more reliable representation of the physical environment in river reaches.

C.1.2 Numerical modelling of hydromorphological variability

C.1.2.1 Model specifications

The simulation of morphodynamic processes using the numerical model SSIIM2 (Olsen, 1991) aims to deliver information about the spatial and temporal distributions of habitat variables to describe the abiotic habitat conditions during the reproduction period of gravel-spawning fish. The general requirements on a numerical model, formulated in Chapter B.1.3, are actualized in this section.

Water depth and flow velocity distribution

The hydraulic characteristics in SSIIM2 are simulated using the full RANS-equations and the k-ε-turbulence model. The simulated flow character on a detailed three-dimensional grid allows an accurate description of varying water depth and flow velocities which are required to represent the hydrodynamic processes during the reproduction process.

Particle size distribution

Two requirements on the particle size distribution have to be considered. The first one includes a reliable representation of the morphodynamic processes and the second one with the habitat requirements of gravel-spawning fish during reproduction. The applied particle size distribution orientates on the Wentworth-Scale (1922) and is listed in Tab.C.1.1.

Table C.1.1: Applied particle size classification to describe morphodynamic processes

Wentworth	cobbles	pebbles				granules	sand			silt
d [mm]	128	64	31.5	16	8	4	2	0.5	0.25	0.063

The entire particle size range comprises all representative sizes in the investigated river reaches of this thesis. During reproduction a proper mix of pebbles, granules and sand is required for spawning while during the incubation period the contents of sand and silt are of major importance. During the emergence period the amounts of granules and small pebbles are significant to provide interstitial pathways for emerging fry (e.g. Bjornn & Reiser, 1991; Kondolf, 2000).

Bed load

Given the wide range of applicability and the good performance in several comparative studies (e.g. Ribberink et al., 2002), the formula of Wu et al. (2000) is applied in this modelling framework to compute bed load with the numerical SSIIM2. Eq.C.1.1 represents the formula to calculate the dimensionless bed load rate Φ_b:

$$\Phi_b = 0.0053 \cdot \left[\left(\frac{n'}{n}\right)^{3/2} \cdot \frac{\tau_b}{\tau_{cr}} - 1\right]^{2.2} \qquad \text{Eq.C.1.1}$$

The ratio of Mannings' roughness of the river bed (n') to Mannings' roughness of the grains (n) multiplied with the bed shear stress (τ_b) is used to calculate a particle shear stress which is similar to the method of Meyer-Peter/Mueller. The non-dimensional excess bed shear stress expressed by the ratio of particle shear stress to critical shear stress minus one is used as an independent parameter in the relationship of determining the dimensionless bed load rate Φ. Inserting Eq.C.1.1 in Eq.A.2.7 gives the final bed load transport by volume per unit time and width. One of the most important features is the hiding/exposure correction factor. The positions of particles in a river bed can be expressed by the exposure height Δe, as it is visualized in Fig.C.1.2. If $\Delta e > 0$ the particle is in an exposed state, while if $\Delta e < 0$ it is in a hidden state. As sediment particles are randomly distributed in a river bed Δe is a random variable that can be approached by the uniform probabilistic function, shown in Eq.C.1.2, where d_i is the upstream particle and d_j the downstream particle.

$$f = \begin{cases} \dfrac{1}{d_i + d_j} & , d_i \le \Delta e \le d_j \\ 0 & \end{cases} \qquad \text{Eq.C.1.2}$$

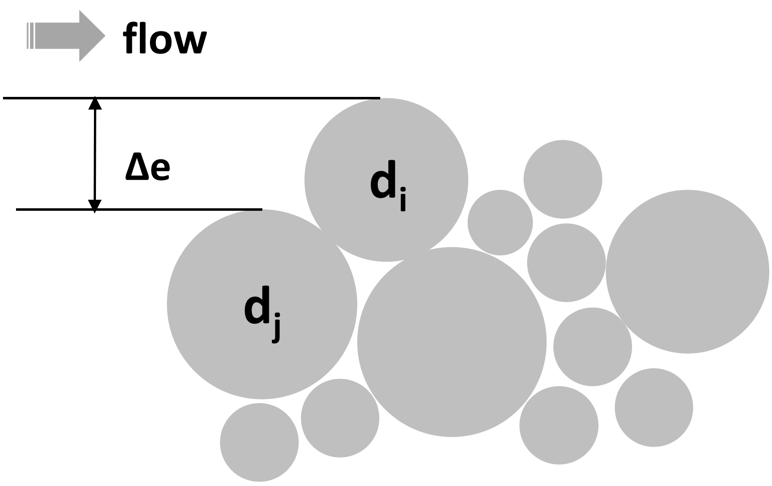


Figure C.1.2: Definition of exposure height Δe in bed material (modified, from Wu, 2007)

Using this probability function Eq.C.1.3 and Eq.C.1.4 describe the total hidden and exposed probabilities of particles by summing over all fractions.

$$p_{hi,j} = \sum_{j=1}^{N} p_{bj} \cdot \frac{d_j}{d_i + d_j} \qquad \text{Eq.C.1.3}$$

$$p_{ei,j} = \sum_{j=1}^{N} p_{bj} \cdot \frac{d_i}{d_i + d_j} \qquad \text{Eq.C.1.4}$$

For uniform sediment particles ($p_{hi}= p_{ei} = 0.5$) the hidden and exposed probabilities are equal, while in non-uniform mixtures the relation is $p_{ei} > p_{hi}$ for coarse particles and $p_{ei} < p_{hi}$ for fine particles. Using these probabilities, a hiding and exposure correction factor is derived to adapt the critical shear stress (Eq.C.1.5).

$$\frac{\tau_{cr}}{(\rho_S - \rho_W) g d_k} = \theta_c \left(\frac{p_{ei}}{p_{hi}}\right)^{-m} \qquad \text{Eq.C.1.5}$$

The exponent (m) is an empirical number that was found to be 0.6 based on calibration of laboratory and field data and can be adapted for calibration purposes (Wu et al., 2000).

Suspended load

The equation of van Rijn (1984) is widely used for simulating suspended loads, and provides information about near-bed concentrations as it is required for analysing sediment infiltration processes. Additionally, the formula is able to deal with multiple particle sizes. Thus it is an adequate approach for the requirements on suspended load simulations in this thesis. The equilibrium sediment concentration $c_{S\delta}$ close to the river bed is defined according to Eq.C.1.6:

$$c_{S\delta} = 0.015 \frac{d^{0.3} \cdot \left(\frac{\tau_b - \tau_{cr}}{\tau_{cr}}\right)^{1.5}}{\delta \cdot \left[\frac{(\rho_S - \rho_W) g}{\rho_W \nu^2}\right]^{0.1}} \qquad \text{Eq.C.1.6}$$

The reference level δ in the van Rijn equation can either be set to the equivalent roughness height or to the half height of bed forms depending on bed form characteristics. As criteria for the incipient motion of suspension, the shear stress approach is applied and should be calibrated according to the particle diameter (Bisantino et al., 2010).

To calculate the vertical sediment concentration profile the formula can be linked to any available approach representing the vertical distributions of sediment concentrations. However, van Rijn (1993) proposed a two-layer relation describing a parabolic-constant distribution of sediment diffusivity as it is given by Eq.C.1.7

$$\varepsilon = \begin{cases} \left[\dfrac{h/z_S - 1}{h/\delta - 1}\right]^{r} & , if \ \dfrac{z_S}{h} < 0.5 \\ \left(h/\delta\right)^{-r} \cdot e^{\left[-4r\left(z_S/h - 0.5\right)\right]} & , if \ \dfrac{z_S}{h} \geq 0.5 \end{cases} \qquad \text{Eq.C.1.7}$$

Eq.C.1.7 specifies a parabolic distribution of concentration for the lower half and a constant value for the upper half of the water column using the Rouse number. It is valid for small volumetric concentration (c_s< 0.001).

Settling velocity

The settling velocity for each particle size is determined using the formula of Zhang (1961) which is, according to Wu (2007), representative for naturally worn sediment particles in laminar and turbulent settling regions (Eq.C.1.8).

$$\omega_s = \sqrt{\left(13.95\frac{\nu}{d}\right)^2 + 1.09\left(\frac{\rho_s}{\rho_w} - 1\right)gd} - 13.95\frac{\nu}{d} \qquad \text{Eq.C.1.8}$$

Porosity

Although the porosity module in SSIIM2 is not extensively tested it is applied in this thesis as it provides highly valuable information about the sediment characteristics of the river bed and can have strong influence on sediment-transport processes, including bed level changes, transport rates and especially sorting processes. The SSIIM2 porosity approach is based on Frings et al. (2011) and uses the geometric standard deviation of a particle size distribution and their percentage of particle sizes less than 0.5 mm (Eq.C.1.9):

$$n_p = 0.353 - 0.068\sigma + 0.146p_{<0.5mm} \qquad \text{Eq.C.1.9}$$

Eq.C.1.9 is a semi-empirical formula which is developed particularly for the sediments of river Rhine and no information is available whether this equation is transferable to other rivers. However, it is assumed that the trends of varying porosities due to sediment infiltration processes are well approximated by this approach.

Layer thickness

According to experimental measurements of Schaelchli (1993) the depth of sediment infiltration can be estimated with Eq.C.1.10 what coincides with observations of both Beschta & Jackson (1979) and Lisle (1989).

$$h_{inf} = 3 \cdot d_m + 0.01 \qquad \text{Eq.C.1.10}$$

Furthermore Schaelchli observed in his experiments that the least-permeable layer is between the surface and the subsurface layer what implies the unhindered transport of depositing fine material through the coarse surface layer. Several preliminary investigations with SSIIM2 to reproduce or approximate this vertical mixing process provided no satisfactory results. This is not surprising as unhindered settling through a surface layer is not realizable in numerical models where sorting processes between surface and subsurface layer are based on the principles of Hirano (1971) or Ribberink (1987). Therefore the active layer thickness in SSIIM2 is chosen to be the depth of sediment infiltration estimated by Eq.C.1.10, while the subsurface layer functions as sediment storage and delivery with a thickness of several meters.

Sediment infiltration

Sediment infiltration is not a common output of numerical approaches dealing with sediment-transport as changes in particle size compositions without bed deformations are not reproducible in numerical models. Therefore in this thesis two strategies to consider sediment infiltration are followed. The first is a combination of numerical modelling with SSIIM2 and the semi-empirical approach of Schaelchli (Chapter B.2.3.1, Tab.B.2.2) whiles in the second the temporal and spatial infiltration masses are simulated directly by SSIIM2 without Schaelchli's equations. The idea of both strategies is to calibrate the simulated infiltration masses of SSIIM2 based on the calculated infiltration masses of the semi-empirical approach of Schaelchli. This assumes that the Schaelchli equations approximate the temporal infiltration processes with a sufficient accuracy, which may be reasonable as his semi-empirical approach is based on the experimental analyses of infiltration processes in a laboratory flume.

The first strategy uses the Schaelchli equations including the seepage volume, infiltration mass and the two infiltration resistances for calculating sediment infiltration using the spatially and temporally varying simulated values of SSIIM2 as input parameters (sediment concentration, ratio d_{10}/d_m, Shields number, water depth). This strategy intervenes at the sediment continuity of SSIIM2 as simulated deposits with SSIIM2 differ from the calculated infiltration masses with the approach of Schaelchli, due to the missing consideration of infiltration resistances in SSIIM2.

The goal of the second strategy is to simulate the sediment infiltration processes directly with SSIIM2 without using the Schaelchli equations. Therefore the infiltration mass is assumed to be the progressive deposition of fine material less than 2 mm in the upper sediment layer. The infiltration mass per time-step is calculated by the following formula:

$$m_k = \Delta p_{<2mm,} \cdot \rho_s \cdot \delta_{SL} \cdot \left(1 - n_p\right) \qquad \text{Eq.C.1.11}$$

The infiltration mass is the difference of fractions with particle sizes less than 2 mm of the actual time-step and the previous time-step ($\Delta p_{<2mm}$) multiplied with sediment density (ρ_s), bed solid fraction ($1-n_p$) and the surface layer thickness (δ_{SL}). Although the dynamic infiltration resistances as well as vertical hydraulic gradients are neglected, the temporal character of the sediment infiltration processes might be reproduced in SSIIM2 due to proper calibration. The direct simulation of infiltration processes has the major advantage that sediment continuity in SSIIM2 is fulfilled.

C.1.2.2 Data requirements

Numerical modelling of morphodynamic processes with SSIIM2

The aforementioned model specifications define the required data to run SSIIM2 for the predefined purposes. The data requirements can roughly be subdivided into initial conditions, boundary conditions and data to calibrate and validate the simulation results. Initial conditions encompass data about river geometry, the horizontal and vertical distribution of sediment particles and an initial water surface and must be specified for each grid cell of the computational mesh. The boundary conditions contain the time-series of varying incoming discharges and sediment fluxes (upstream boundary) as well as time-series about the corresponding water levels at the downstream boundary. These boundary conditions define the temporal resolution and depend on the hydrologic variability of the investigated river reach. While for calibrating hydraulics the water levels are used, the calibration of morphodynamic processes is performed on bed level changes and particle size compositions.

Semi-empirical approach of sediment infiltration (Schaelchli, 1993)

For the calculation of sediment infiltration using the semi-empirical approach of Schaelchli, additional information is required about the initial permeability of the surface layer and regarding the temporally and spatially varying vertical hydraulic gradients for each grid cell.

C.1.2.3 Model outputs

The numerical model outputs of SSIIM2 provide the hydromorphological variability for each grid cell of the computational mesh. In terms of hydraulics this comprises the time-series of water depths, water levels, flow velocities (in several layers), kinetic energy (turbulence intensity) and secondary flow. In terms of morphodynamics information is provided about bed level changes, varying particle size compositions and distributions (horizontally and vertically), sediment concentrations of each fraction, porosity and infiltration masses. These variables are used to describe the changing abiotic environment over time and are used for deriving further input variables for habitat modelling. Hence, this numerical modelling step predominantly addresses hypothesis 1. Restrictions are made regarding the required assumptions for simulating the sediment infiltration processes. This includes mainly the assumption that sediment infiltration occurs in the surface layer instead of between the surface and subsurface layer and the neglect of lateral bed filtration processes in the gravel-framework.

C.1.3 Simulation of hyporheic variability

C.1.3.1 Model specifications

The simulation of the interstitial habitat suitability (IHS) aims to describe the abiotic interstitial conditions in form of an indicator for the hyporheic variability in gravel river beds during the incubation period of gravel-spawning fish. Contrary to existing approaches which consider on the one hand only sedimentological factors (e.g. particle size analyses, sediment infiltration) or on the other hand are static and not predictable (e.g. mapping of colmation), the fuzzy-approach to simulate IHS-values associates both. This approach results in a dynamic prediction of most relevant abiotic processes during the incubation period. The idea of this procedure implies not to describe the colmation process itself but to consider the abiotic interstitial habitat demands during incubation of gravel-spawning fish.

Parameter selection and description

One important aspect in defining habitat variables is the available information about the biological response of indicator species to a given habitat variable. For instance, the sediment characteristics in terms of pore space and packing can also be described with the bed solid fraction or porosity which is directly simulated by SSIIM2. However, no biological information is available in order to answer the question which grade of porosity is required in each development stage during incubation. Therefore the choice of habitat variables has to be orientated on both the ability of variables to describe a certain process and on the available information about the biological response of indicator species.

The requirements of abiotic parameter selection to describe the quality of interstitial habitats are specified in Chapter B.2.5. Therefore the following three parameters are prioritized:

- permeability,
- interstitial temperature and
- hyporheic respiration.

The parameter *permeability* indicates the spatial and temporal morphological variability describing the feasibility of oxygen-rich water to enter the hyporheic zone and to transport metabolic waste products downstream. The change of permeability in gravel-bed rivers can be estimated using the Kozeny-Carman-Equation (Eq.C.1.12).

$$k_P = \frac{g}{\nu} \cdot 0.0083 \left(\frac{n_P^3}{(1-n_P)^2} \right) d_{10}^2 \qquad \text{Eq.C.1.12}$$

Several studies have been performed to compare the predictability of empirical permeability equations with measured permeability indicating an adequate performance for the Kozeny-Carman-Equation for a broad range of sediment samples (e.g. Odong, 2008; Ishaku et al., 2011). Although important parameters for permeability like packing or particle shape are not included in it, the equation is useful in simulations examining general trends of changing interstitial sediment characteristics (Johnson, 1980). Using the numerical simulation results of SSIIM2 for bed solid fraction (1-n_p) and fine particle fractions (d_{10}), the permeability can be computed in each bed cell of the computational grid.

The *interstitial temperature* is a key variable indicating development rates of eggs and larvae during incubation. Moreover, the interstitial temperature gives upper and lower lethal and sub lethal limits during the reproduction process which are determined by metabolic bottlenecks. This parameter is largely determined by the mixing processes of ground and surface water (up- and downwelling, Chapter A.2.2.5). In this approach the spatial distribution of interstitial temperatures is assumed to be constant, however, the seasonal interstitial temperature changes during the reproduction period are considered.

Finally, the *hyporheic respiration*, aggregating the oxygen demands of sedimentary, biological and chemical processes, is used as a habitat variable defining the total oxygen demand in the hyporheic interstitial due to biogeochemical processes. The respiration is usually measured as dissolved oxygen mass per volume and time. To get an idea about the spatial heterogeneity of this parameter, the measured respiration rates can be converted into area-based values considering additionally the thickness of the investigated sediment layer, its porosity and percentage of particles smaller than 8 mm (Uehlinger et al., 2003; Doering et al., 2011). These parameters describe the available surface areas of particles for microbial growth and development (Jones et al., 1995). Furthermore it is assumed that for particles larger 8 mm the available surface area is small compared to the whole sediment volume which represents a more or less inactive metabolic volume with low respiration rates (Doering et al., 2011). Eq.C.1.13 represents the conversion of measured volume-based respiration rates to area-based respiration rates resulting in different respiration values for each cell of the computational grid.

$$R_{H,A} = R_{H,V} \cdot \left(1 - n_p\right) \cdot \delta_{SL} \cdot p_{<8mm,} \cdot \qquad \text{Eq.C.1.13}$$

The area-based respiration rate strongly depends on interstitial temperature - the major driver for the magnitude of metabolic processes. Temperature dependence is compensated for using Arrhenius-function (Doering, 2007) to normalize the respiration rate based on a reference temperature, T_{RH}, as given by Eq.C.1.14.

$$R_{H,A}\left(T_{R_H}\right) = R_{H,A}(T) \cdot {c_A}^{T-T_{R_H}} \qquad \text{Eq.C.1.14}$$

The constant c_A corresponds to a value of 1.072, which is a frequently applied value for biological reactions (Doering, 2007).

The input habitat variables for the fuzzy-based computation of the interstitial habitat suitability are calculated with the previously described equations encompassing the most relevant abiotic processes to describe the interstitial habitat. The next section presents the fuzzification of each habitat variable with their combined effects of the proposed habitat variables on the interstitial habitat via a fuzzy-rule-system.

Fuzzification of interstitial habitat variables

For the definition of membership functions of habitat variables two requirements have to be considered. In particular, both the entire range of occurring values in a study site and the entire range of the requirements of an indicator species have to be covered by membership functions. The number of membership functions and the degree of overlapping define the fuzziness of the approach and allows for implementation of uncertainty. This comprises predominantly the cognitive uncertainty (knowledge about habitat requirements of indicator species) and the uncertainty of input parameters (uncertainty of modelling and measurements).

Permeability

Tab.C.1.2 provides general information about the requirements of salmonids on permeability during reproduction. The biological response in literature is given mainly qualitatively using verbal expressions or quantitatively using survival rates. For comparison reasons all values found in literature are transformed to qualitative expressions (‘low’, ‘medium’, ‘high’) as they are applied in the fuzzy-approach.

Table C.1.2: Habitat requirements of salmonids for the habitat variable permeability during the reproduction period

permeability [cm/h]	biological response	Reference
< 100	very low	Crisp (1996)
< 200	very low	McCuddin (1977), Tagart (1976)
< 600	low	Peterson (1978)
< 1000	low	McCuddin (1977), Chapman (1988), Knopf (2010)
< 2000	low	Wickett (1954), Rubin (1998)
2500-4700	medium/high	Jordan & Beland (1981)
1000-10000	medium	McCuddin (1977), Chapman (1988), Knopf (2010)
> 10000	high	McCuddin (1977), Chapman (1988), Knopf (2010)
> 24000	very high	McNeil & Ahnell (1964)

Although the values in Tab.C.1.2 were determined for different salmonid species the general trend indicating higher suitability for increasing permeability is clearly visible which presents the basis of the fuzzy-set generation (Fig.C.1.3).

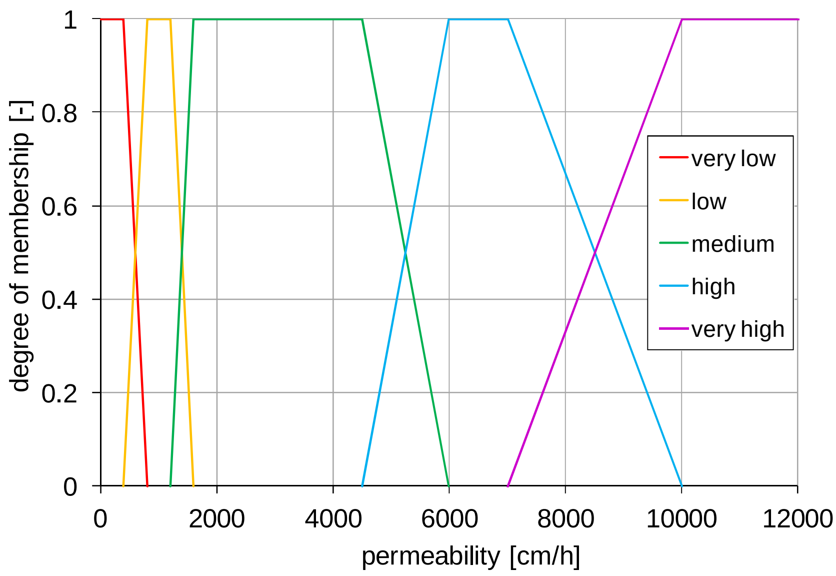


Figure C.1.3: Fuzzification of the habitat variable permeability as an input parameter to calculate the interstitial habitat suitability (IHS)

Fig.C.1.3 gives for lower permeability (< 2000 cm/h) a higher number of membership functions to distinguish between permeability ranges that are not suitable (‘very low’) and those that have a low suitability (‘low’). In contrast, the ranges for ‘medium’ and ‘high’ permeability are significantly larger as in these ranges salmonids are not that vulnerable to permeability. Highest suitability is achieved for permeability values > 10000 cm/h.

Interstitial temperature

Similarly to the permeability, Tab.C.1.3 summarizes the habitat requirements on interstitial temperature during the incubation period. The temperature requirements differ among the different salmonids species considerably. The values given in Tab.C.1.3 are valid for brown trout as this is the indicator species for the case study at the River Spoel (see Chapter D.2).

Table C.1.3: Habitat requirements of brown trout for the habitat variable interstitial temperature during the reproduction period

temperature [°C]	**biological response**	**reference**
< 1	very low	Humpesch (1985)
1-5	low	Elliot (1981)
4-6	very high	LUBW (2005)
7	very high	Jungwirth & Winkler (1984)
8-10	very high	Ojanguren & Brana (2003)
7-12	high	Varley (1967)
> 10	medium	Humpesch (1985)
12-13	very low	Jungwirth & Winkler (1984)
> 15	very low	Humpesch (1985), Ojanguren & Brana (2003)

The above listed interstitial temperatures are mostly valid for the pre-hatching stage. After hatching, a brown trout is able to resist more extreme temperatures. For example, Ojanguren & Brana (2003) give an optimal temperature range for the pre-hatching period between 8 °C and 10 °C while 6 °C-12 °C for the post-hatching period. Fig.C.1.4 shows the fuzzification of the interstitial temperature.

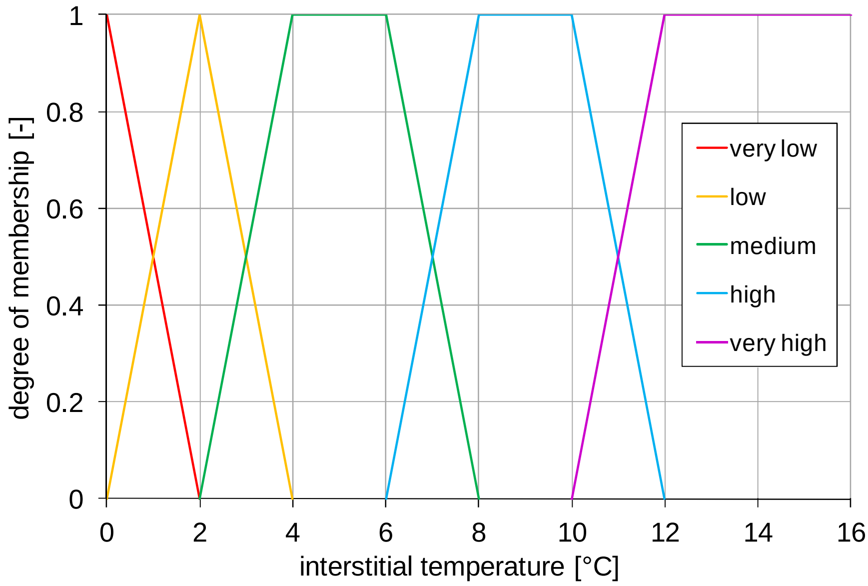


Figure C.1.4: Fuzzification of the habitat variable interstitial temperature as an input parameter to calculate the interstitial habitat suitability (IHS)

The defined fuzzy-sets shown in Fig.C.1.4 describe the upper and lower temperature limits by the membership functions ‘very low’ and ‘very high’, while the optimum in respect to a habitat suitability is defined by the sets ‘medium’ and ‘high’. The ‘medium’ membership function encompasses a lower suitability for the pre-hatching stage due to the higher vulnerability than the ‘high’ fuzzy-set.

Hyporheic respiration

The definition of a fuzzy-set for the variable hyporheic respiration is difficult as no general information about habitat requirements is available from the scientific literature. However, critical dissolved oxygen levels for the different development stages during reproduction are frequently published allowing the computation of critical respiration rates if concentrations of dissolved oxygen (DO) and information about sediment characteristics are available. Tab.C.1.4 shows critical DO-levels for salmonids and corresponding critical respiration rates assuming a typical volumetric respiration of 15 mgO_2/lh, a layer thickness of 0.15 m, a porosity of 20 % and a percentage of particle sizes less than 8 mm of 15%. Although the presented values in Tab.C.1.4 are based on calculations the values are better interpreted as estimated values based on the above mentioned assumptions and their dependency on interstitial temperature. However Tab.C.1.4 gives a first impression of critical hyporheic respiration values and can be interpreted as follows: for given sediment characteristics and a mean volumetric respiration, the values in the third column give the maximum allowed respiration to maintain the critical oxygen level specified in the first column (from scientific literature). Given the influence of sediment characteristics on aerial hyporheic respiration, these values are highly site-specific and thus are not transferable between different river types. Fig.C.1.5 gives the fuzzification of the hyporheic respiration using three membership functions.

Table C.1.4: Habitat requirements of salmonids for the habitat variable hyporheic respiration during the reproduction period

dissolved oxygen [mg/l]	reference	hyporheic respiration [gO_2/m^2d]	biological response	life stage
< 1	Alabaster & Loyd (1980)	32	very low	early
< 5	Sowden & Power (1985), Dirksmeyer (2008)	19	very low	eggs
5-7	Dirksmeyer (2008), Heywood & Walling (2007)	19-13	medium	hatching
> 7	Crisp (1996), Kondolf (2000)	13	high	hatching
> 8	US EPA (1986)	10	very high	hatching
10	Lindroth (1942)	6.5	very high	hatching
3-5	Rombough (1988)	26-19	high	larvae

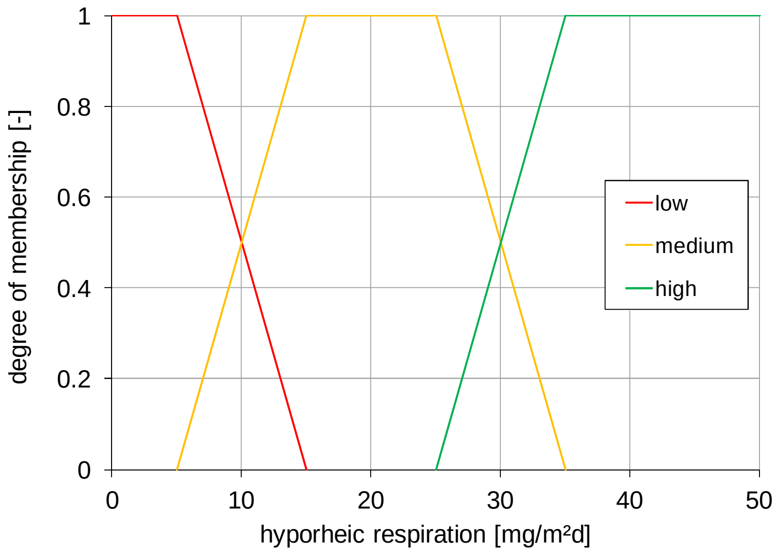


Figure C.1. 5: Fuzzification of the habitat variable hyporheic respiration as an input parameter to calculate the interstitial habitat suitability (IHS)

The hyporheic respiration as a habitat variable contains only three membership functions. This is on the one hand due to the high uncertainty in determining the thresholds for critical respiration values, and on the other hand due to statements of several authors who concluded that a differentiation of critical oxygen levels in three categories is sufficient for general assessments of reproduction (Dirksmeyer, 2008; Heywood & Walling, 2007): whereby dissolved oxygen values between 0-5 mg/l give more or less 100 % mortality, the range of 5-7 mg/l show varying mortalities and above 7-10 mg/l the oxygen-levels are not critical for reproduction success.

Fuzzy-Rules/Inference-system

Contrary to the previously defined fuzzy-sets of habitat variables which are valid for the total incubation period, the fuzzy-rules are specified for each development stage during the incubation period. According to Fig.A.2.9, the incubation is subdivided into the eyed-egg stage, hatching stage and larval stage. The input arguments (habitat variables) are not independent, for instance, both the permeability as well as the interstitial temperature have an effect on hyporheic respiration. However, in contrast to statistical methods the fuzzy-approach is able to deal with dependent variables as long as this dependency is explicitly considered in the generation of the fuzzy-rules themselves. Tab.C.1.5 presents selected fuzzy-rules leading to 'high' and 'low' interstitial habitat suitability from the entire rule-sets for the different stages during development. The entire fuzzy-rule-systems are listed in Appendix 2.1.

Table C.1.5: Examples of fuzzy-rules to calculate the interstitial habitat suitability (IHS) during reproduction period of gravel-spawning fish considering different life-stages

ID	permeability	interstitial temperature	hyporheic respiration	interstitial habitat suitability	life-stage
h_1	high	medium	low	very high	hatching
h_2	low	medium	medium	medium	hatching
h_3	very low	medium	high	very low	hatching
e_4	high	low	medium	very high	eyed-egg
h_5	high	low	medium	medium	hatching
l_6	high	low	medium	high	larvae

The first three rules in Tab.C.1.5 define the IHS-values for the hatching stage which has the highest requirements on hyporheic habitat. For example, rules h_{1-3} can be read as follows: A 'high' permeability allowing the infiltration of oxygen-rich water to intrude the hyporheic zone combined with a 'medium' interstitial temperature which lies in the optimal range for hatching and a 'low' hyporheic respiration describing little biogeochemical activities result in a 'very high' IHS-value (rule h_1). High sediment infiltration rates may lead to reductions in the permeability with correspondingly higher respiration rates given to more available surface areas for microbial growth leading to a 'medium' IHS-value (rule h_2). In case of strong sediment infiltration severe reduction of permeability to the membership function 'very low' may result. The IHS-value also yields 'very low' as such permeabilities lead to high mortality rates and hence, dominate the other habitat variables (rule h_3).

The rules e_4, h_5, and l_6 show the responses of different life-stages during incubation to the same rule which is describing an average interstitial condition. The eyed-eggs have relatively low abiotic requirements due to the early stage of development and the protecting egg-shell resulting in a 'very high' IHS-value (rule e_4). However, the oxygen demand is continuously increasing during the egg development until the most critical hatching stage during the incubation period, where the highest requirements are reached. Consequently, the IHS-value of the hatching stage is specified as 'medium' (rule h_5). Although the oxygen demand is increasing in the larval stage, the habitat requirement of larvae is lower compared to the hatching stage, as on the one hand the oxygen is obtained by the gills (which is much more effective compared to the diffusion through the egg shell) and on the other hand the larvae have a limited mobility allowing them to avoid low-oxygen zones in the river bed. Therefore, the rule l_6 gets a ‘high’ IHS-value.

C.1.3.2 Data requirements

The data required to calculate the hyporheic variability in form of IHS-values are based on the results of the numerical model SSIIM2 supplemented with the field measurements of interstitial temperature and hyporheic respiration. While the interstitial temperature can easily be measured using data-logging techniques, measurements of hyporheic respiration are more difficult and more cost- and labour intensive. However, as the above mentioned approach uses sedimentary characteristics and the Arrhenius-equation to estimate the temporal and spatial heterogeneity of hyporheic respiration rates, the number of respiration measurements can be significantly reduced. Nevertheless, the more measurements are available the better the model predictions can be verified. Furthermore information about the habitat requirements for each habitat variable in each life-stage during the incubation period is needed to formulate the corresponding fuzzy-sets and fuzzy-rules. This is performed based on literature values and biological expert-knowledge.

C.1.3.3 Model outputs

Based on the specified fuzzy-set for the IHS-values (Appendix 2.7) the obtained crisp results can be in a range from 0.16 to 0.84, whereby an IHS-value of 0.16 indicates a ‘low’ quality of the interstitial habitat and an IHS-value of 0.84 indicates a ‘very high’ quality. These numbers result from defuzzification of the fuzzy-sets for IHS-values without scaling the values on a range between 0 and 1. The fuzzy- approach to calculate the IHS-values is performed in each time-step and in each grid cell to get both the spatial and temporal changes of IHS-values. The simulated IHS-values reflect the hyporheic variability and subsequently its effects on the development of eggs and larvae during the incubation period. However some restrictions should be pointed out. The approach does not explicitly consider the mixing processes between surface and groundwater which are governed by the vertical hydraulic gradient. These exchange processes affect predominantly the spatial distribution of interstitial temperatures and the oxygen availability in the interstitial. However, regarding the main objective – to increase the indication value of interstitial predictors – the simulated IHS-values contain significantly more information compared to previous approaches as they include not only sedimentary characteristics but also information about interstitial temperatures and hyporheic respiration. Therefore this modelling step addresses hypothesis 2.

C.1.4 Physical habitat modelling

C.1.4.1 Model specifications

The physical habitat simulation tool CASiMiR with its multivariate fuzzy- approach is used to link the simulated habitat variables with the biotic response during the whole reproduction period. This encompasses the spawning period, the incubation period as well as the emergence period, whereby the incubation period is further subdivided into the stages eyed-eggs, hatching and larvae (Fig.C.1.1). For each life stage during reproduction a proper choice of habitat variables is needed with a corresponding formulation of fuzzy-sets and fuzzy-rules. As brown trout is the target species in the main case study of this thesis (Chapter D.2), all requirements are formulated for brown trout. The resulting fuzzy-sets and fuzzy-rules are presented in Appendices 2.2 – 2.6.

Spawning habitat

In Tab.A.2.4 the habitat variables for the selection of spawning-sites of gravel-spawning fish encompassing predominantly hydraulic and sediment characteristics are listed. Interstitial parameters like the vertical hydraulic gradient or permeability are no dominant habitat variables for spawning site selection as they play only a role for spawning in terms of test diggings. Furthermore the interstitial parameters are much more relevant during the incubation period. Although the availability of cover is also an important habitat variable to provide shelter, it is not considered here as in the investigated study site (Chapter D.2) no predators and no high flows occur during the spawning period (personnel comment of Johannes Ortlepp). Additionally, the available space for spawning is not considered. This is due to the primary objective of the study to simulate the abiotic conditions of physical habitat and not the effects of species competition about most suitable spawning sites. Next to hydrodynamic parameters, the particle size distribution is a key variable for spawning site selection. The available habitat requirements regarding the sediment characteristics are listed in Tab.C.1.6.

Table C.1.6: Habitat requirements of brown trout on particle sizes in river bed for the selection of spawning sites

percentage [%]	particle size	biological response	reference
< 5	< 2	very high	Raleigh et al. (1986)
> 15	< 2	low	Louhi et al. (2008)
> 20	< 2	very low	Soulsby et al. (2001)
25	4-16	high	Mull & Wilzbach(2007)
25	16-32	high	Fluskey (1989)
40-50	2.2-22	high	Peterson (1978)
35	32-64	high	Fluskey (1989)
-	10-80	high	Blohm et al. (1994)
-	8-128	high	Mull & Wilzbach(2007)
-	10-64	high	Bjornn & Reiser (1991)
> 40	d_{max}	low	Wooster et al. (2008)
> 50	$d_{suitable}$	high	Bjornn & Reiser (1991)

The available information about sediment preferences of spawning brown trout (Tab.C.1.6) indicate that percentages > 15 % of particle sizes < 2 mm are avoided in spawning sites which is also used as a summarized value in Dirksmeyer (2008). For other particle sizes or ranges it is difficult to derive general trends as the reported values show a wide variance, especially for the upper limit of suitable sediment ranges. This is not surprising as the maximum tolerated particle size significantly depend on fish length (Kondolf & Wolman 1993). According to Kondolf et al. (2008) the maximal movable particle size is about 10 % of fish length. Combining this information with the maximum tolerated amount of d_{max} (Wooster et al., 2008) and the minimum percentages for $d_{suitsable}$ (Bjornn & Reiser, 1991), the habitat requirements on sediment characteristics can be formulated.

This is accounted for in a two-stage fuzzy approach to simulate spawning habitat suitability (HSI_{spawn}). In a first step the particle size distribution describing the amounts of certain particle ranges are evaluated resulting in a spawning sediment index (SSI) while the second step combines the SSI-values with the hydraulic variables flow velocity and water depth. Fig.C.1.6 illustrates the two-stage fuzzy approach for spawning including all the considered habitat variables.

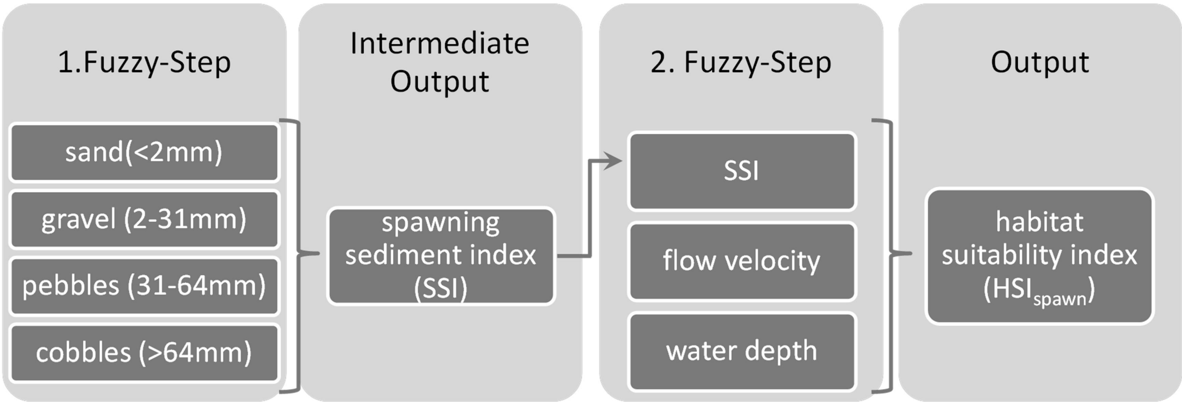


Figure C.1.6: Two-stage fuzzy-approach to simulate the habitat suitability for spawning (HSI_{spawn})

The first fuzzy-step evaluates the sediment characteristics using four sediment classes covering the whole particle size distribution listed in Tab.C.1.1. This is important to account for spawning habitat requirements on river bed sediments like the maximum amount of fine material (< 2 mm) or the maximum particle size (< 64 mm) a female salmonid is able to move during the digging process of redds. The second step considers the varying hydraulic conditions to account for sufficient manoeuvrability during spawning and the downstream transport of fines during digging. This two-stage fuzzy-model requires the formulation of fuzzy-sets for the fractional amounts for each of the four sediment classes as well as for the habitat variables in the second fuzzy-step. The applied fuzzy-sets and fuzzy-rules are presented in Appendices 2.2 - 2.6.

Incubation habitat

The key habitat variable defining the HSI-values during incubation is the interstitial habitat suitability (IHS, Chapter C.1.3) which accounts for the hyporheic variability during incubation including changes in permeability, interstitial temperature and hyporheic respiration. According to Tab.A.2.5 additional factors during incubation are relevant. The first ones are sediment-transporting events which may erode the protecting sediments of redds and displace eggs or larvae while the second one is groundwater infiltration into redds what can result in significant reductions of oxygen supply.

To account for occurring erosion the bed level change is compared to egg burial depths. Typical egg burial depths for brown trout are between 5 cm and 25 cm (Crisp & Carling, 1989). However an average egg burial depth of 12 cm is assumed in this approach with minimal values of 2 cm and a maximum of 23 cm as it is reported by (Grost et al. 1991) who analysed more than 80 redds of brown trout. As in natural redds the eggs are not located at a constant depth and larvae have limited mobility in the interstitials even small bed level changes may lead to displacements. This becomes even more relevant as mechanical damage is likely to occur as soon as a bed movement starts due to sediment-transport. To consider the potential influence of groundwater entering redds, the direction of the vertical hydraulic gradient is applied as habitat variable. If the vertical hydraulic gradient becomes positive groundwater with more or less no dissolved oxygen enter the surface water preventing the oxygen transport to eggs and larvae during incubation. As long as the vertical hydraulic gradient remains constant or the direction of the gradient is not reversed, the role of surface hydraulics is not dominating the incubation habitat. However, if considering not only the direction of vertical hydraulic gradients but also the magnitude of gradients, then the relevance of surface hydraulics increases, as for higher negative gradients (downwelling) more oxygen-rich surface water is entering the gravel-framework. Considering the bed level change as well as the direction of the vertical hydraulic gradient as additional habitat variables to the interstitial habitat suitability, the HSI-values during incubation are simulated by another two-stage fuzzy-approach as it is shown in Fig.C.1.7.

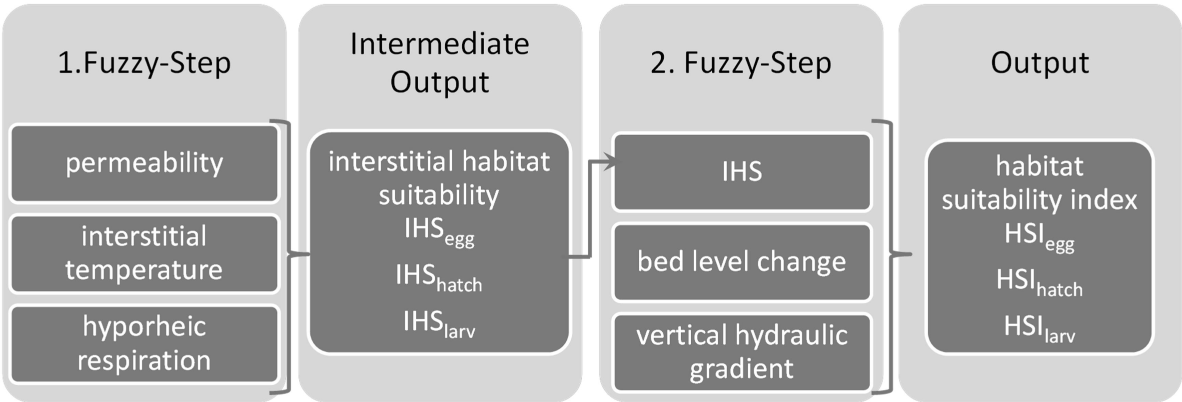


Figure C.1.7: Two-stage fuzzy-approach to simulate the habitat suitability during incubation period (HSI_{egg}, HSI_{hatch}, HSI_{larv})

Although the incubation period comprises several life-stages, the parameter selection for each stage is identical but the different habitat requirements during incubation are considered in the fuzzy-rules. Therefore the results of the first fuzzy-step are IHS-values for each life-stage which subsequently leads to different HSI-values at the end of the second fuzzy-step. Another aspect to be considered is that the obtained HSI-values cannot increase within one life-stage, as a limited habitat condition cannot be compensated by a better habitat condition at a following time-step. Using this two-stage fuzzy-approach it is assumed to reflect the most relevant abiotic factors and processes affecting the quality of interstitial habitats during incubation. While the fuzzy-sets for the first step are visualized in Chapter C.1.3 the fuzzifications and rules for computing the second step are given in Appendix 2.7.

Other relevant factors like the residence time of interstitial water or the exposure duration of eggs and larvae to limited abiotic conditions are not considered in the approach. Moreover, a dissolved oxygen model balancing the oxygen consumption of eggs and larvae, the hyporheic respiration as well as reaeration rates of surface waters entering the gravel beds in combination with changing sediment characteristics would lead to a benefit of the model. This bears additionally large uncertainties and many assumptions and is neglected in this modelling framework but might be a subject for future research.

Emergence habitat

The emergence habitat describes the abiotic conditions at the end of the incubation phase. The objective of this modelling step is rather to simulate the ability of larvae to emerge from the interstitial zone into the free water zone than to simulate the timing of emergence which is largely determined by the strength of larvae and interstitial temperatures (see also Chapter A.2.2.5). Therefore the sediment characteristics - in terms of connected pores - providing unhindered pathways towards the free water zone are a key aspect to be considered. This aspect would be best approximated using the porosity as an indicator of the sediment characteristics. However, no biological data that correlate porosity with emergence success is available. Similarly, the parameter permeability is also not applicable as scientific literature provides only information about correlations to ETF-survival and not solely to emergence success. Nevertheless, Rubin (1998) observed successful emergence of hatched fry at sediments with a geometric mean diameter (d_g) of more than 15 mm that provide sufficient pore space and in sediment with a $d_g < 6.4$ mm as the particles are light enough to be displaced by the emerging fry. However, a $d_g < 6.4$ mm is generally avoided by salmonids and most probably all eggs would die before hatching due to lack of oxygen. Bjornn (1968) found for percentages between 30 % and 40 % of particles less than 6.4 mm impeded emergence, while Witzel & MacCrimmon (1981) found increasing emergence success (2 %-96 %) for sand fractions which were reduced from 60 % to 20 %. This is in substantial agreement with Kondolf et al. (2008) who recommended using fractions between 3 mm and 10 mm to assess excessive amounts of particles that might block pores for successful emergence. Therefore in this approach both the d_g as well as the percentage of particles less than 8 mm are used to characterise the sediments for emergence purposes. Furthermore it has to be ensured that no displacement and no mechanical damage occur due to sediment-transport which is approximated by the variable bed level change. Fig.C.1.8 shows the applied parameter for calculating the HSI_{emerg} in a single fuzzy-step.

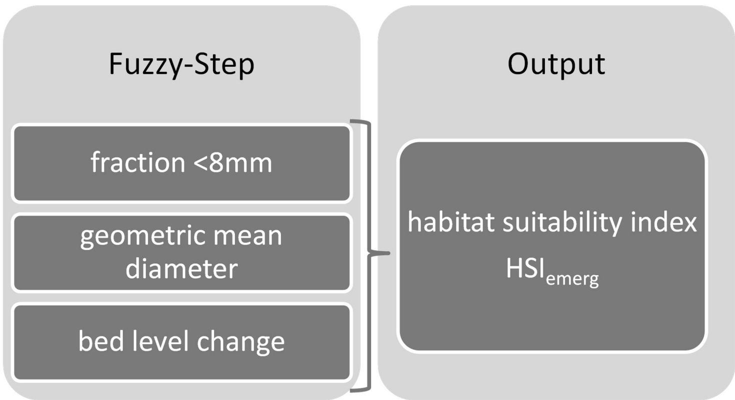


Figure C.1.8: Fuzzy-approach to simulate the habitat suitability of the emergence period (HSI_{emerg})

In this calculation step it is assumed that the fractional percentage of particles smaller than 8 mm combined with the geometric mean diameter and the presence/absence of bed level change describe the habitat characteristics during the emergence period. The fuzzification of parameters as well as the rule-set is given in Appendix 2.8. According to Schiemer et al. (2003) the period after emergence shows high mortality rates as the emerged fry are exposed to abiotic and biotic threads of the free water zone and many die because of starving, predators or physiological damages. These effects are not considered in this modelling framework. The investigated period ends with the ability to emerge from the gravel bed into the free water zone and any further effects after emergence are not taken into account. This implies that surface hydraulics play a minor role in determining the emergence habitat.

C.1.4.2 Data requirements

For simulation of HSI_{spawn} all required data are delivered by the numerical model SSIIM2. The first fuzzy-step, to obtain the spawning sediment index (SSI), requires the fractions of each particle size of the four sediment classes. The second fuzzy-step requires additionally the hydraulic parameters such as water depth and flow velocity which are also direct outputs of SSIIM2.

Next to the data requirements to simulate the interstitial habitat suitability, information about the bed level changes and the direction of the vertical hydraulic gradient during the incubation period is required. The bed level change is a direct output of SSIIM2 while the vertical hydraulic gradient is based on measurements. Therefore techniques with different efforts might be applied. However, as only the direction of the vertical hydraulic gradient is required, it is sufficient to measure the difference between the surface water level and the groundwater level to identify areas with up- and downwelling.

For the simulation of habitat quality during the emergence period, the required data can also directly be derived from outputs of SSIIM2. While the fractional percentage of particles smaller than 8 mm and the bed level change are the direct outputs, the geometric mean diameter is calculated based on Eq.B.2.1 using all simulated fractional percentages of all particle sizes.

Next to abiotic data, information about the combined effects of habitat variables on the different HSI-values are needed which is defined in the fuzzy-rules and fuzzy-sets. These are based on literature values and on biological expert-knowledge.

C.1.4.3 Model outputs

The output of physical habitat modelling is given in HSI-values ranging from 0.16 (‘low’ suitable) to 0.84 (‘very high’ suitable) for each life stage during reproduction. The computations are done for each grid cell in each time-step providing detailed information about the spatial and temporal variations of HSI-values. This modelling step addresses hypothesis 3 to provide the required HSI-values for aggregation to a total reproduction habitat suitability which is subject of the last part in the modelling framework.

C.1.5 Simulation of reproduction habitat suitability (RHS)

The aggregation of the simulated HSI-values to a reproduction habitat suitability (RHS) comprehends the summarized effects of all varying abiotic conditions during the reproduction period on the habitat quality for self-reproducing gravel-spawning fish. Therefore the HSI-values of each life stage during reproduction have to be connected in a chronological order. In doing so it is very important to consider that a ‘low’ HSI-value during a life-stage, describing limited abiotic conditions, cannot be compensated by a ‘high’ HSI-value of a following life-stage. For instance, a ‘low’ HSI-value during the hatching period cannot be compensated by ‘high’ HSI-values during the larval stage. This implies to use a multiplicative relationship of the minimal HSI-values in each life-stage for aggregation. Hence, Eq.C.1.15 describes the multiplicative connection to compute the aggregated reproduction habitat suitability (RHS).

$$RHS = \prod_{i=1}^{n} \min(HSI_i) \qquad \text{Eq.C.1.15}$$

In Eq.C.1.15, i is an index for the different investigated life-stages (spawning, eyed-egg, hatching, larvae and emergence) and n is the total number of investigated life-stages (n=5).

The multiplicative linkage is performed in each grid cell providing detailed information about spatial distribution of reproduction habitat suitability which is the summarized output of the multi-step habitat modelling framework.

C.2 Model applicability and limitations

To avoid misinterpretations and to provide a brief outlook about the accuracy that can be expected in applying the proposed multi-step habitat modelling framework, this chapter deals with the applicability and limitations of the framework including spatial and temporal dimensions as well as bearing uncertainties.

Spatial and temporal dimensions

Spatial dimension:

The modelling framework is an approach dedicated to micro-habitat modelling allowing investigations on a spatial scale up to approximately 1 km. The limiting factor regarding the total length of a river reach is mainly determined by the available computational power to meet on the one hand the requirements of temporal dimensions and model complexity and on the other hand to represent hydromorphological processes correctly. The size of elements to discretisize the river reach depends on the heterogeneity of the river reach but can be recommended between 0.5 – 1.0 m laterally and 1 – 2 m longitudinally.

Temporal dimension:

A central objective of this modelling framework is to reflect the impact of temporally and spatially changing abiotic environment on habitat conditions for the reproduction of gravel-spawning fish. This includes the hydrological variability with high and low flow periods as well as flood events with subsequently changing sediment characteristics and their impact on reproductive habitat conditions. Therefore, the minimal total simulation period of the modelling framework comprises the whole reproduction period. To include the effects of abiotic variability on spawning habitats it is recommended to include the last-occurred flood event before spawning to simulate mixing and sorting processes of multiple particle sizes in the investigated river reach. The selected numerical time-step have to be short enough to reflect the abiotic variability and to ensure numerical model stability but also long enough to allow simulations over the months of reproduction. In general, the time-step should not be larger than one hour to represent the abiotic variability adequately.

Model accuracy and uncertainties

The accuracy of the simulation results is subject to numerous uncertainties arising from data sampling, numerical modelling and habitat modelling. Accurate measurements of abiotic habitat variables in rivers and particularly in the hyporheic interstitial with the required spatial and temporal resolution are still a challenge. Uncertainties occur on the one hand due to the applied measurement techniques and on the other hand due to the frequency and the spatial resolution of measurements. Uncertainties in numerical modelling occur through the simplification of abiotic processes by mathematical description including discretization techniques, empirical functions and the definition of initial and boundary conditions. Finally, the uncertainties in habitat modelling emerge from the definition of physical-biotic relationships that are not exactly known or cannot be described using exact functions or equations that are valid for different types of rivers (cognitive uncertainty). Given these uncertainties the modelling framework does not aim to simulate exact survival rates but expresses the results in habitat suitability indices reflecting purely the impact of varying abiotic habitat conditions. Moreover, the modelling framework does not intend to simulate the reproduction habitat of single redds but addresses the suitability of typical reproductive areas comprising several redds and to investigate how these areas react on changing morphodynamic processes induced by floods or low flow periods.

Model limitations

The multi-step habitat modelling framework includes numerous limitations. The modelling framework is purely based on the simulation of abiotic aspects and neglect biological interactions which might greatly affect the reproduction success. For instance, important aspects like species competition which affect fish behaviour during the selection of spawning sites (Groot, 1996), the abundance of egg predators like worms (oligochaeta) which can detrimentally reduce survival rates during the incubation period (Meyer, 2003) or the effect of changing environmental conditions on growth rates during the reproduction process which determines the resistivity of eggs and larvae (Bjornn & Reiser 1991) are not included in the modelling framework. Another aspect is the effect of diseases like fungal or bacterial infections of eggs and larvae which can also significantly reduce the number of emerging fry (Kent, 2011).

The abiotic conditions of reproductive habitats are not fully reflected within this modelling approach. Firstly, severe assumptions and simplifications of the sediment infiltration processes are required to compute the infiltration masses numerically. Secondly the hydrological exchange processes between groundwater and surface water and the interstitial flow paths are not fully considered affecting the changes of interstitial temperatures and of oxygen supply to eggs and larvae. Especially the resulting availability of dissolved oxygen as a function of egg and larval consumption, hyporheic respiration and reaeration is not explicitly implemented within this modelling framework but approximated via the simulation of the interstitial habitat suitability. Another aspect not considered is the ‘cleaning’ of redds and the subsequent reduction of fine sediments during the digging process of spawning redds as well as the specific redd topography which favours the infiltration of oxygen-rich surface water to the egg pockets.

Given these limitations the simulation results can only be interpreted regarding the included abiotic habitat variables and how indicator species will react given to changes of these habitat variables during reproduction and do not draw any assertions regarding real survival rates. This aspect is also reflected in the term habitat suitability index as this term gives only the suitability of an abiotic environment and no information about biomass, abundance and survival.

PART D: MODEL APPLICATIONS

Presented in this part is the multivariate habitat modelling framework with its different modelling steps. Firstly, the experimentally investigated infiltration processes in a flume with controlled boundary conditions, performed by Schaelchli in 1993, are simulated using the 3D-sediment-transport model SSIIM2 in order to test whether the sediment infiltrations processes can be reproduced numerically (Chapter D.1). The second element of this part is the case study at the River Spoel in the Alps of Switzerland (Chapter D.2). Following the description of the study site, this chapter includes the abiotic and biotic monitoring, the calibration and validation of morphodynamic processes using SSIIM2 (effects of artificial flooding and sediment infiltration during the reproduction period) and the fuzzy-approach to simulate the interstitial habitat suitability for the life-stages during the incubation period. The physical habitat model, CASiMiR, is applied to simulate all life-stages during the reproduction period including the spawning stage, the incubation stage, and the emergence stage with a subsequent aggregation of the obtained HSI-values to a reproduction suitability index (RHS).

D.1 Simulation of laboratory experiments

The main objective of the numerical simulation of the laboratory experiments of Schaelchli (1993) is to test whether SSIIM2 is capable to simulate the temporal and spatial behaviour of sediment infiltration processes. Hence, the experimental setups are transferred into the numerical model SSIIM2. In contrast to the equation-set of Schaelchli (Chapter B.2.3.1), the numerical model SSIIM2 does not consider any infiltration resistance which have to be compensated for by the calibration process. This section provides detailed information about the modelling procedure, the calibration process and gives additional information about the sensitivity in terms of model-specific parameters and input parameters.

D.1.1 Model setups

D.1.1.1 Experimental setup

Schaelchli examined in 1993 the sediment infiltration processes and the consequential reduction of permeability at the Laboratory of Hydraulics, Hydrology and Glaciology of the Federal Institute of Technology in Zuerich, Switzerland. To derive his equation-set for sediment infiltration he examined over 25 simulation runs conducted in a rectangular flume with a length of 8.0 m and a width of 0.5 m. The flume is instrumented with a recirculating system for water and suspended load, a sediment feeding machine and two measuring areas (0.15 m²) for the pressure of the interstitial water at different sediment depths and the volume of infiltrating flow. The sediments originate from three natural rivers and two artificial mixed particle size distributions. The initial gravel bed was formed at high flows to create an artificial armoured layer. His developed equations (Tab.B.2.2) are based on the assumptions that the interstitial zone between surface and ground water is saturated, the river bed does not dry up, and that no gravel is transported over the armoured layer (Schaelchli, 1995).

D.1.1.2 Numerical setup

Input data

For the numerical reproduction of the physical experiments eleven simulation runs were selected and calibrated using three different particle size distributions with varying boundary conditions. Tab.D.1.1 gives an overview of the applied data.

Table D.1.1: Overview of applied data for simulating sediment infiltration processes in the laboratory flume using the numerical model SSIIM2

ID	d_{10} [mm]	d_{60} [mm]	d_{90} [mm	d_m [mm]	d_{10}/d_m [-]	Q [m³/s]	δ_{SL} [m]	c_S [kg/m³]	i [m]	h [m]	I [%]
1.1	0.31	26	64	27	0.0115	0.015	0.091	0.025	0.36	0.06	0.63
1.2	0.31	26	64	27	0.0115	0.015	0.091	0.070	0.36	0.06	0.63
1.3	0.31	26	64	27	0.0115	0.015	0.091	0.090	0.36	0.06	0.63
1.4	0.31	26	64	27	0.0115	0.053	0.091	0.400	0.45	0.15	0.63
1.5	0.31	26	64	27	0.0115	0.053	0.091	0.350	0.42	0.15	0.63
2.1	0.40	33	76	32	0.0125	0.046	0.106	0.180	0.65	0.12	1.3
2.2	0.40	33	76	32	0.0125	0.060	0.106	0.600	0.65	0.14	1.3
2.3	0.40	33	76	32	0.0125	0.024	0.106	0.120	0.24	0.08	1.3
3.1	0.41	25	40	20	0.0205	0.060	0.070	0.050	0.76	0.11	1.9
3.2	0.41	25	40	20	0.0205	0.060	0.070	0.180	0.76	0.11	1.9
3.3	0.41	25	40	20	0.0205	0.030	0.070	0.080	0.33	0.07	1.9

The ratio d_{10}/d_m encompasses values between 0.0115 and 0.0205 with slopes (I) between 0.63 % and 1.9 % and with discharges (Q) between 0.015 m³/s and 0.060 m³/s. The sediment concentrations (c_s) range from 0.025 kg/m³ to 0.600 kg/m³ and the hydraulic gradient (i) varies from 0.24 to 0.76. The water depth (h) is in a range of 0.06 m to 0.15 m and the layer thickness (δ_{SL}) varies between 0.07 m and 0.106 m. Based on the hydraulic computations the range of bottom shear stresses ranges between 4.00 N/m² and 18.25 N/m². Given this choice of simulations runs it is assumed that the ranges of variables governing the sediment infiltration are represented in a sufficient variability to test and calibrate the numerical simulations of sediment infiltration processes with SSIIM2.

Initial conditions

In the physical experiments an armoured layer was created using high flows before the infiltration investigations were started. As no data about this initial flushing is provided, the armoured layer is calculated based on the particle size distribution of the subsurface layer (Tab.D.1.1) using the equations of Guenter (1971). All particle size distributions applied in the simulation runs consists of six particle sizes whereby five particle sizes are used for the initial bed material and one for the suspended load. An overview of the initial particle size distributions and the resulting armoured layers is given in Appendix 3.1. The thickness of the active layer δ_{SL} is calculated using Eq.C.1.10 which describes the expected depth of infiltrating fine material. The subsurface layer functions as a sediment storage and delivery component and consists of the particle size distributions listed in Tab.D.1.1 and Appendix 3.1. The thickness of the subsurface layer is in all simulations runs specified with 2.0 m.

Boundary conditions

Constant discharges at the upstream boundary with corresponding water levels at the downstream boundary are specified to define the hydraulic boundaries. For the suspended load only concentrations were available without information regarding the specific particle sizes and size-related fluxes. Although Schaelchli provided a range of particle sizes for suspended load which were measured during the experiments, it is not explicitly clear if this range in- or excludes the resuspended bed material. Therefore the incoming sediment concentrations (given in Tab.D.1.1) are specified for one additional particle size that is initially not present in the bed material. This allows an easier observation and interpretation of the ongoing sedimentation processes. The final particle size of the incoming sediment is found through the calibration process.

Discretization

The flume is spatially discretized with an adaptive unstructured grid having 80 grid cells in longitudinal, 10 grid cells in lateral and a maximum of 10 grid cells in vertical direction, giving a total number of 8000 grid cells. The average length of one grid cell is 0.1 m, the average width 0.05 m and the height depends on water depth that defines the maximal number of grid cells in vertical location. Fig.D.1.1 shows an example of the three-dimensional grid with lateral profiles with simulated horizontal flow velocities for simulation run 1.1.

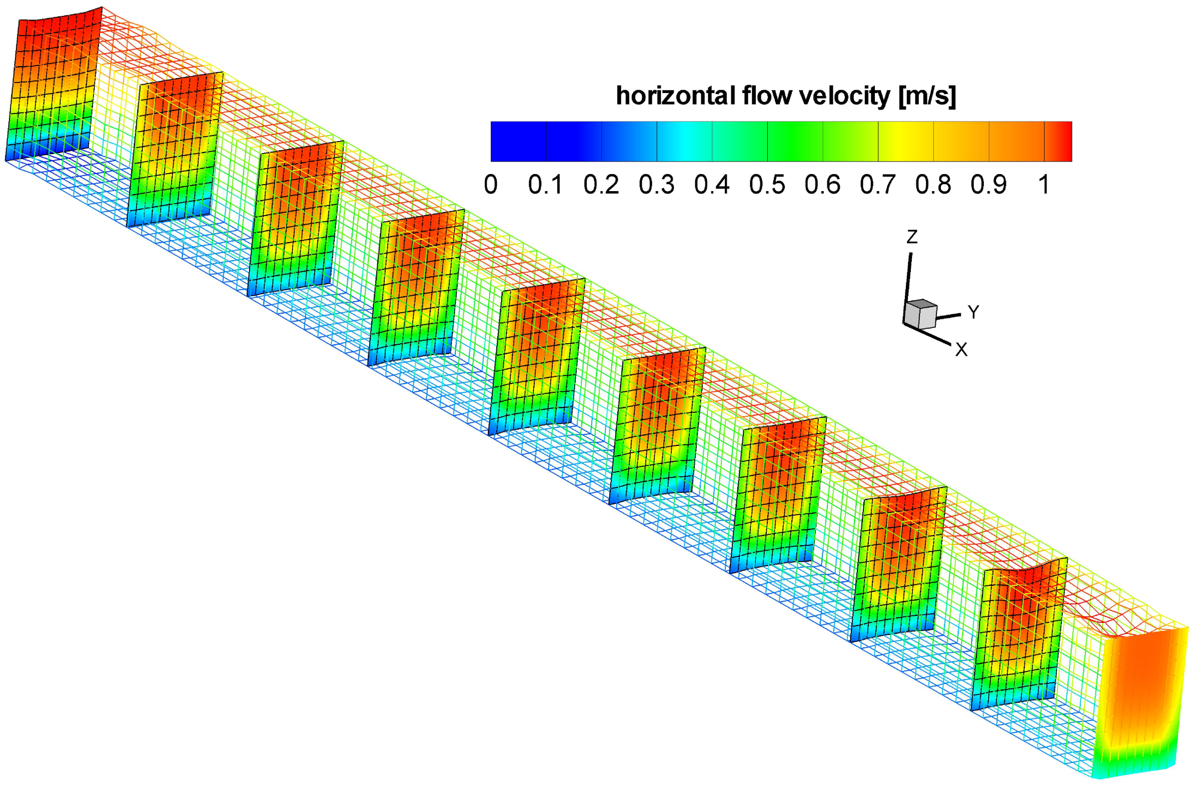


Figure D.1.1: Example visualization of the three-dimensional grid of the rectangular flume with simulated horizontal flow velocities for simulation run 1.1

Sediment-transport

With the focus of sediment infiltration processes and the assumption of Schaelchli (1993) that no gravels are transported over the armoured layer, the suspended load transport is computed using the equation of van Rijn (1984, Eq.C.1.6) to define the near-bed sediment concentrations and thus, the delivery of suspended particles to the gravel bed. The sediments in suspension are transported using the convection-diffusion equation (Eq.A.3.1) and the resulting sediment concentrations are compared with the simulated near-bed concentration (Eq.C.1.6) to decide whether a particle becomes deposited or stay in suspension. The dimensionless Shields number is calculated based on an implemented parameterisation of the Shields curve (Fig.A.2.2) while the settling velocities are computed using Zhang's formula (1961, Eq.C.1.8).

D.1.2 Results of numerical simulation of infiltration processes

D.1.2.1 Calibration

Given the numerous empirical functions and assumptions included in numerical modelling of sediment-transport processes as well as the high uncertainty in data sampling the calibration process is a difficult but indispensable step for proper modelling. To calibrate SSIIM2 for sediment infiltrating processes the deposition masses of suspended material is compared to the infiltration masses of the approach of Schaelchli. Morphodynamic numerical models generally provide several factors to adjust the simulation results to observed values. In addition to the selection of a sediment-transport formula a typical calibration method is the adaptation of the critical shear stress which can be adjusted directly or through the application of hiding/exposure functions. Further calibration factors are the thicknesses of the surface and subsurface layer as well as other empirical parameters specified in the selected sediment-transport formula.

Hydraulic calibration

The hydraulics of all simulation runs are calibrated by comparing the measured water levels with the simulated ones. The simulated water levels are adjusted by changing the roughness values, which are specified as k_s-values in SSIIM2. Best agreements are obtained using the d_{90} of the particle size distribution in the surface layer. This corresponds to the grain roughness which is a reliable value, as the river bed consists of coarse gravels and the effect of form roughness in the rectangular flume is low.

Calibration of sediment infiltration

Based on the assumption that the numerically simulated deposition of fine material in the surface layer corresponds to the semi-empirical infiltration masses of the approach of Schaelchli (Chapter C.1.2.1), the largest restriction in the numerical model SSIIM2 is the lacking consideration of an infiltration resistance. To compensate for the lacking infiltration resistance the application of hiding/exposure functions affecting the critical shear stress offers an appropriate opportunity for calibration. The hiding/exposure function of Wu et al. (2000, Eq.C.1.5) provides a calibration exponent (m) to regulate the degree of hiding/exposure and thus enables a controlling feature for the equilibrium between deposition and resuspension of fine sediments which defines the limiting state for sediment infiltration processes.

To visualize the strong effect of the calibration exponent (m) in the hiding/exposure function, Fig.D.1.2 presents simulation results of run 2.1 with exponents varying between 0.0 and 0.9.

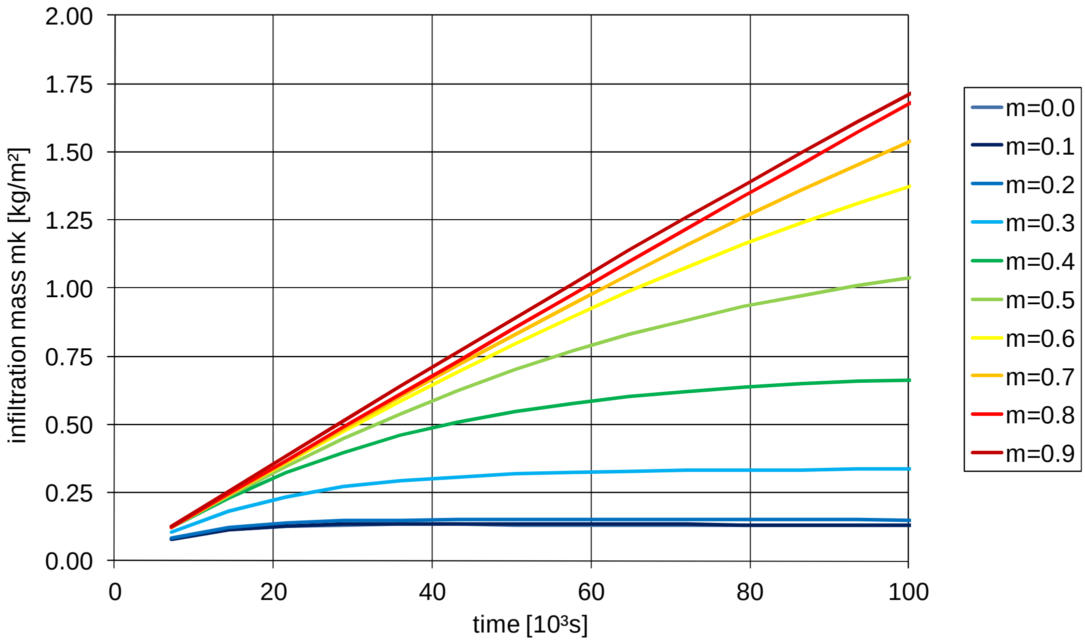


Figure D.1.2: Effect of calibration exponent in the hiding/exposure function of Wu et al. (2000) on infiltration masses

Fig.D.1.2 emphasizes the strong influence of the exponent using the hiding/exposure function of Wu et al. (2000) on both the magnitude of sediment infiltration and the temporal behaviour of the infiltration process. If hiding/exposure is not considered, SSIIM2 simulates a small deposition which remains constant after a short time-period (m=0.0). After this short time period the continuously incoming suspended loads are in equilibrium with the resuspended material resulting in no further depositions. The effect of hiding/exposure is represented by the simulations with increasing exponents ($0.1 \leq m \leq 0.9$). The deposited fine particles that are hidden behind larger particles do not easily become resuspended. Correspondingly, the equilibrium between the depositing and resuspended material is not achieved in the considered simulation period for very high values of the exponent (m=0.8, m=0.9). The angle of slopes in the curves of Fig.D.1.2 for exponents ranging from 0.3 to 0.7 occurs from slowly approaching the equilibrium state. This interpretation corresponds to the observations of Schaelchli (1995) and Banscher (1976) who found no further infiltration in cases of equilibriums between resuspension and deposition. Balancing the in- and outflowing sediment fluxes at the boundary conditions confirm this interpretation. While for low exponent values the amount of outflowing sediments are approximately equal to the inflowing sediments, the outflowing sediments for large values of the exponent are considerable smaller indicating higher depositions and lower resuspensions (Tab.D.1.2).

Table D.1.2: Balance of sediment in- and outflow for different exponents of the hiding/exposure-function of Wu et al. (2000) in run 2.1 after approximately 28 hours

	sediment inflow [kg]	sediment outflow [kg]	deposited sediments [kg]
m=0.0	993.6	992.8	0.8
m=0.5	993.6	988.2	5.4
m=0.9	993.6	985.4	8.2

Noteworthy are the selected particle sizes for the added suspended material with corresponding settling velocities. Given the lack of information regarding the incoming particle sizes, it is part of the calibration process to determine the particle size for suspended load. Therefore, the amounts of depositions after two hours are compared to the infiltration mass of Schaelchli with subsequently adaptations of the particle size to obtain matching values. Best results were found in a particle range of 0.01 mm to 0.02 mm. Although these particle sizes are typical suspended load fractions (Schaelchli, 1993), they are comparatively small and out of the measured range in the flume (Schaelchli, 1993). A reason could be that the measured suspended particles sizes include larger parts of resuspended bed material which are included in the specified sediment concentrations in Tab.D.1.1.

Based on these preliminary investigations, the calibration of all simulations runs listed in Tab.D.1.1 are performed by adjusting the exponent (m) of the hiding/exposure function of Wu et al. (2000). Fig.D.1.3 gives the results of calibration comparing exemplary the simulated deposition masses with the semi-empirical infiltration masses for the runs 1.1, 2.1 and 3.1 encompassing three different particle size distributions.

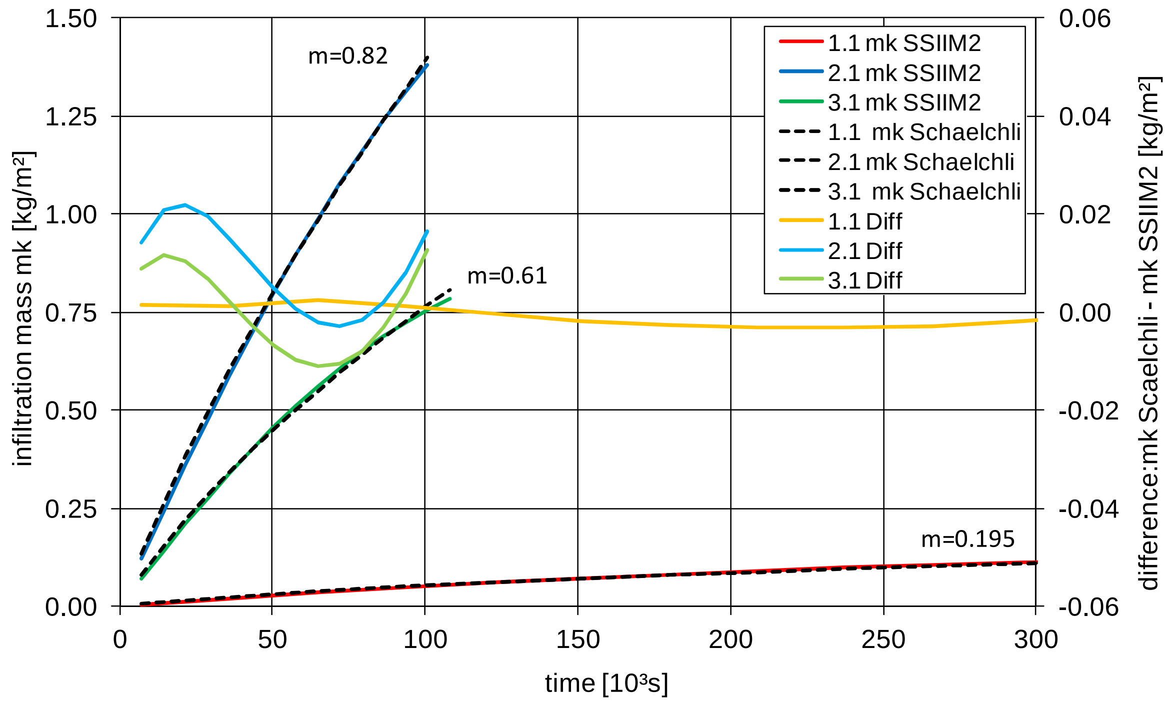


Figure D.1.3: Comparison of numerically simulated deposition masses with semi-empirically calculated infiltration masses for the simulation run 1.1, 2.1 and 3.1

In Fig.D.1.3 the three simulations indicate a satisfying calibration result. The maximum deviation for simulation run 1.1 (m=0.195) is less than ± 0.005 kg/m² while for run 2.1 (m=0.61) and run 3.1 (m=0.82) it is approximately ± 0.01 kg/m². It is noticed from the figure that all difference-curves show a more or less distinctive horizontal s-shape which is caused by slightly underestimating the semi-empirical values at the beginning, slightly overestimating in the middle, and slightly underestimating the semi-empirical results at the end of the investigation period. This indicates that the temporal behaviour of the infiltration process is not exactly reproduced numerically. Nevertheless, the calibration results are within the limits of measuring accuracy and it can be concluded that with adjustments of the exponent of the hiding/exposure function the semi-empirical solutions of Schaelchli (1993) can adequately be reproduced using the numerical model SSIIM2.

For further analyses concerning the reproduction of gravel-spawning fish the porosity and permeability are of crucial importance. To visualize the effects of simulated sediment infiltration both the bed solid fractions (1 – porosity) and permeability are shown in Fig.D.1.4.

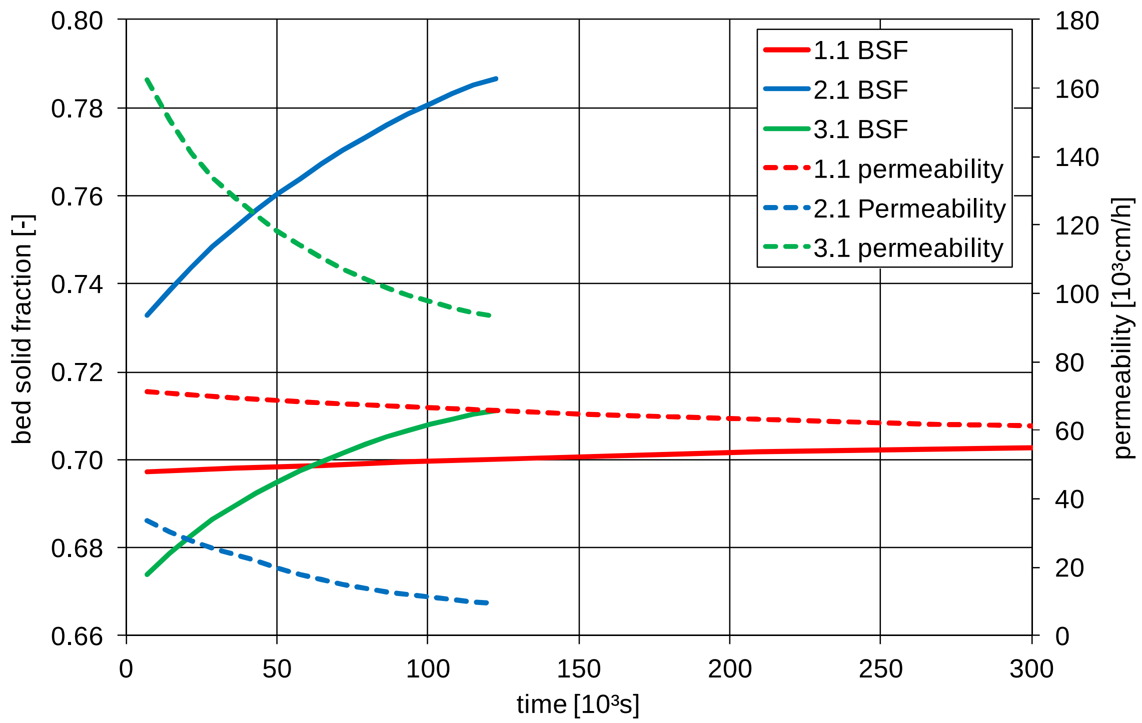


Figure D.1.4: Effect of sediment infiltration on bed solid fraction and permeability for simulation runs 1.1, 2.1 and 3.1

The bed solid fractions in Fig.D.1.4 are continuously increasing, reflecting the reduction of porosity (Eq.C.1.9) due to progressive sediment infiltration. Further, the slope of each curve reflects the temporal behaviour of the sediment infiltration process which is highest for simulation run 2.1 and lowest for simulation run 1.1 which corresponds to the infiltration masses in Fig.D.1.3. Similarly the permeability (Eq.C.1.12) is reduced in varying dimensions according to the sediment infiltration. While for simulation run 1.1 the total reduction of porosity is less than 1 %, the porosity for 2.2 is reduced by approximately 5 %. Distinctively higher is the influence of sediment infiltration on permeability with significantly decreasing values for simulation runs 2.1 and 3.1 which is explained by the change in porosity and the reduction of d_{10} due to increasing amounts of fine sediments in the river bed. The relatively high values obtained for the porosities and permeability are caused by the very coarse surface layer. A verification of these simulation results is not possible due to lacking observed data.

Each simulation was calibrated separately, and the following step is to investigate whether a correlation to the infiltration resistance - which is not included in SSIIM2 - can be found. According to Schaelchli (1993) the total infiltration resistance is the sum of the infiltration resistance of the clean riverbed (=void of fine material) and the continuously increasing resistance due to deposited fines (= specific resistance). This specific infiltration resistance aggregates the influence of the ratio d_{10}/d_m, the vertical hydraulic gradient, the Shields parameter and the solid Reynolds-number on sediment infiltration processes (see also Chapter B.2.3.1). In Fig.D.1.5 the correlation between the calibrated hiding/exposure exponents and the calculated specific infiltrations resistance is visualized for all eleven numerical simulations.

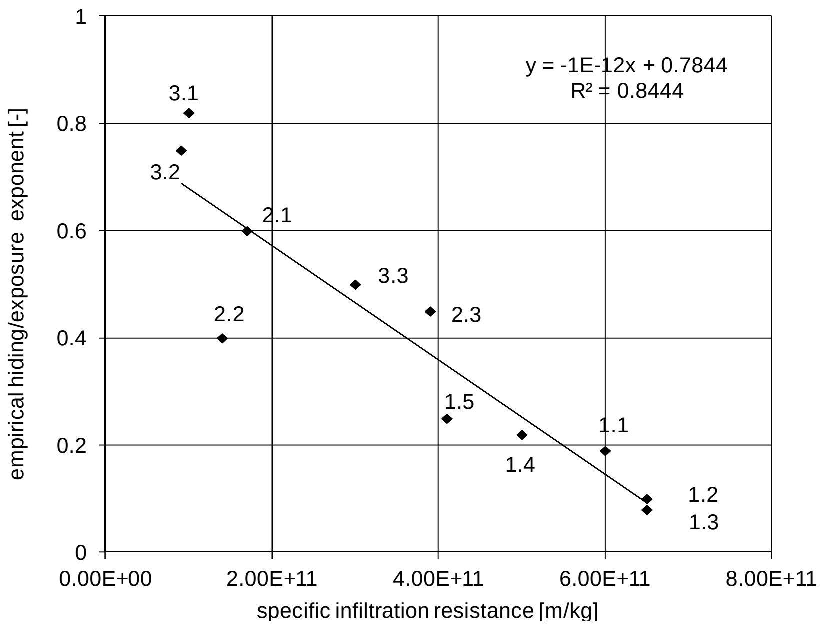


Figure D.1.5: Correlation of calibrated exponents of the hiding/exposure functions of Wu et al. (2000) with semi-empirically calculated specific infiltration resistances of Schaelchli equations (1993)

The correlation pictured in Fig.D.1.5 between the exponent of hiding/exposure and the specific infiltration resistance can be characterized as moderate. The applied exponents of hiding/exposure range from 0.08 to 0.82. The lowest calibrated exponents are applied for the simulation runs 1.1 - 1.3 which are characterized by a low sediment infiltration given to the small vertical hydraulic gradient and shallow slope while the highest values are obtained for the runs 3.1 and 3.2 that have the highest vertical hydraulic gradient and the highest discharge and slope. Although the correlation indicates a clear trend of decreasing exponents for increasing infiltration resistances, there are outliers which cannot be neglected (e.g. 2.2 and 3.1 have similar infiltration resistances but large discrepancies in the calibrated exponents). The reasons for the outliers are mainly:

- insufficient data for the initial sediment conditions of the river bed at the beginning of infiltration experiments and missing particles sizes of suspended load
- the exponent of the hiding/exposure function is static and not able to sufficiently reflect the dynamically varying infiltration resistance
- the highly dynamic character of sediment infiltration cannot be reproduced by simply adjusting one calibration parameter

Although each simulation run can be calibrated separately the moderate correlation indicates that other factors and processes affect the sediment infiltration processes which are not considered yet during calibration. Therefore a sensitivity analysis is performed to check on the one hand the influence of other calibration factors and on the other hand the uncertainty regarding the input parameter to allow a more robust estimation of sediment infiltration.

D.1.2.2 Sensitivity analysis

To test the influence of the numerous parameters affecting sediment infiltration processes two sensitivity analyses are performed. The first is dealing with model-specific parameters which additionally could be used for calibration while the second sensitivity analysis includes variations of the governing input parameters to get an idea of the uncertainty. For each investigated parameter a variation range is specified whereby the minimum and maximum values are simulated and compared to the calibration result. Both sensitivity analyses are performed for the simulation run 2.1. Tab.D.1.3 gives the investigated parameters for the model-specific and input-specific sensitivity analyses with the examined variation ranges.

Table D.1.3: Applied data ranges for the sensitivity analyses of model-specific and input parameters regarding the numerical simulation of sediment infiltration processes

	model-specific parameters				**input-parameters**			
	ω[cm/s]	δ_{SL}[m]	k_s[m]	Wu[-]	Q[m³/s]	c_s [kg/m³]	d_{10}/d_m[-]	I[%]
min	0.005	0.05	0.050	0.4	0.23	0.15	0.08	0.008
cal	0.010	0.10	0.078	0.6	0.46	0.18	0.15	0.013
max	0.015	0.15	0.150	0.8	0.69	0.21	0.30	0.018

The model-specific parameters comprise typical calibration parameters for morphodynamic modelling. The settling velocity ω is a key factor to determine the delivery of suspended load to the river bed and, especially for very fine particles, the empirical equations to determine the settling velocity show significant variations. The active layer thickness δ_{SL} is also a common calibration parameter as it determines the time-scale of mixing processes (Mosselmann, 2007). The roughness k_s is commonly used to calibrate hydraulics but also has a strong influence on the bottom shear stress. Lastly the exponent of hiding/exposure (Wu et al. 2000) is investigated which affects the critical Shields stress according to Eq.C.1.5. Figure D.1.6 presents the results of the sensitivity analysis for the model-specific parameters.

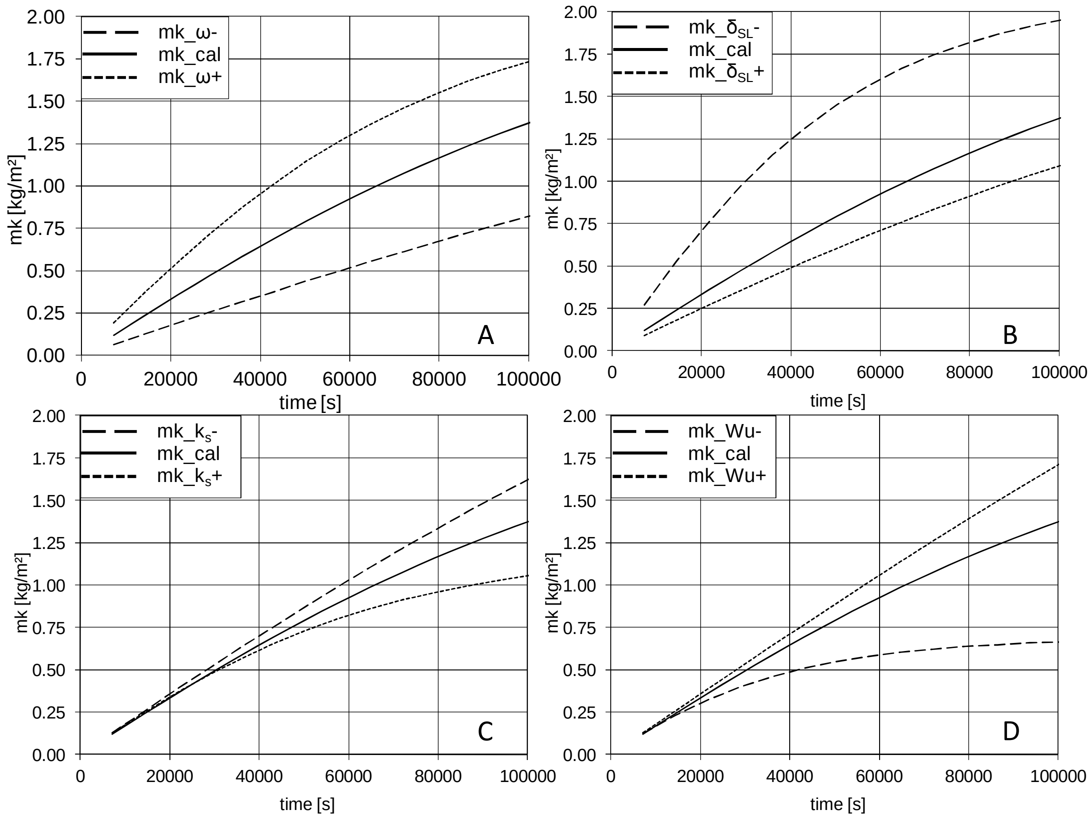


Figure D.1.6: Influence of model-specific parameters on sediment infiltration: A settling velocity, B active layer thickness, C roughness, D exponent hiding/exposure

In addition to the effect of the exponent of the hiding/exposure function, Fig.D.1.6 illustrates that both the magnitude and the temporal process of sediment infiltration are affected by the other three calibration factors. The higher settling velocities (A) produce higher rates of deposition, but additionally affect the shape of the temporal progress of deposition, which is indicated by decreasing sedimentation rates at the end of the simulation run. This is in contrast to the smaller settling velocities which show a more uniform deposition rate. This effect can also be observed for the active layer thickness (B). The run with a small active layer thickness is marked by high deposition rates at the beginning and very low deposition rates at the end of the simulation run, while for a larger thickness the deposition rate remains constant. This is explained by the fact that in a smaller layer the same absolute deposition leads to a quicker increase of the fractional amount compared to thicker layers. A change in roughness (C) affects the bottom shear stress that leads to higher and more static deposition rates for small roughness values and to decreasing deposition rates for high roughness values. High roughness values induce higher turbulences and increase the kinetic energy keeping the sediment particles in suspension. The effects of the exponent of the hiding/exposure function are given in Chapter D.1.2.1. The influence of model-specific parameters on porosity and permeability are shown in Appendix 3.2 and 3.3.

To provide an overview of the results of the model-specific sensitivity analysis on infiltration mass, porosity, and permeability, Fig.D.1.7 summarizes the results for a specified time-step (t=79200s). Visualized in the figure are the absolute percentage deviations from the calibration result.

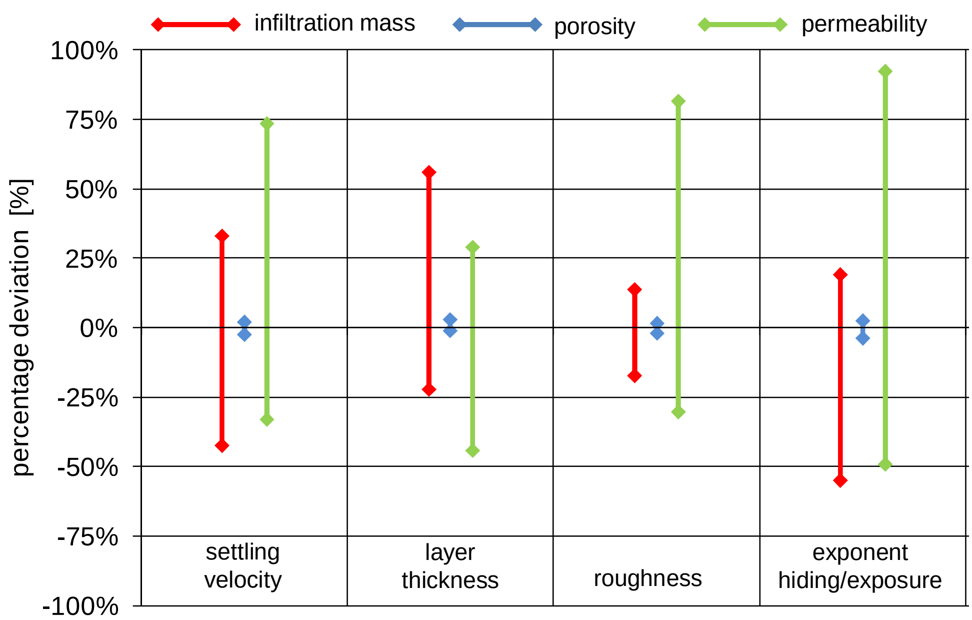


Figure D.1.7: Summarized results of the model-specific sensitivity analysis with effects on infiltration masses, porosities and permeability

The obtained range of results for the simulations with minimum and maximum values of each variable gives an indication of the total influence of each variable on infiltration masses, porosities and permeability. The influence on infiltration masses is relatively similar for the settling velocity, layer thickness and hiding/exposure function (approximately 75 %) while for the roughness the influence is considerably lower (31 %). The effect of sediment infiltration on porosity is indicated to be between 3 % and 5 %, while the variations in permeability are indicated to be between 73 % and 141 %. This implies that even low changes of porosity have a detrimental impact on permeability. This is reasonable as the volume of fine sediments in a coarse surface layer leads only to minor changes on porosity but significantly affects the feasibility of water travelling through the interstices. This aspect is considered in the Kozeny-Carman-Equation (Eq.C.1.12) where porosity and d_{10} are the two dominating variables.

Considering all these factors in the calibration process and their interactions may better explain and improve the correlation shown in Fig.D.1.5. However, for the modelling purpose in this thesis, the most suitable calibration factor is still the exponent of the hiding/exposure function given to following reasons:

- settling velocity: although shape, density, and presence of other particles affect the settling velocity, the most dominant parameter for settling is the particle size. Hence, the settling velocity can be regarded as a physical attribute of particle sizes. Greater modifications of the settling velocity mean to change this physical relationship which reduces its suitability for calibration.
- active layer thickness: the thickness of the active layer is as a common calibration parameter but is not chosen in this case as the applied thicknesses correspond to the depth of infiltration which is a predefined value according to Eq.C.1.10.
- roughness: the roughness is used to calibrate the hydraulic pattern. A change in roughness will not only change the bottom shear stress but also flow velocities and water depth. Thus, the roughness is only used to calibrate hydraulics.

To finally evaluate the results obtained from this sensitivity analysis it can be concluded that the exponent of the hiding/exposure function has the largest influence on the simulation results. In addition, the sensitivity analysis show that for the chosen parameter ranges the results of numerical modelling can be significantly adjusted by calibration. It should be noted that care must be taken to keep the calibration values within a range of physical meaning.

The summarized results of the sensitivity analysis for the input parameter are shown below (Fig.D.1.8), while the temporal variations of the investigated parameters are visualized in the Appendices 3.4-3.6.

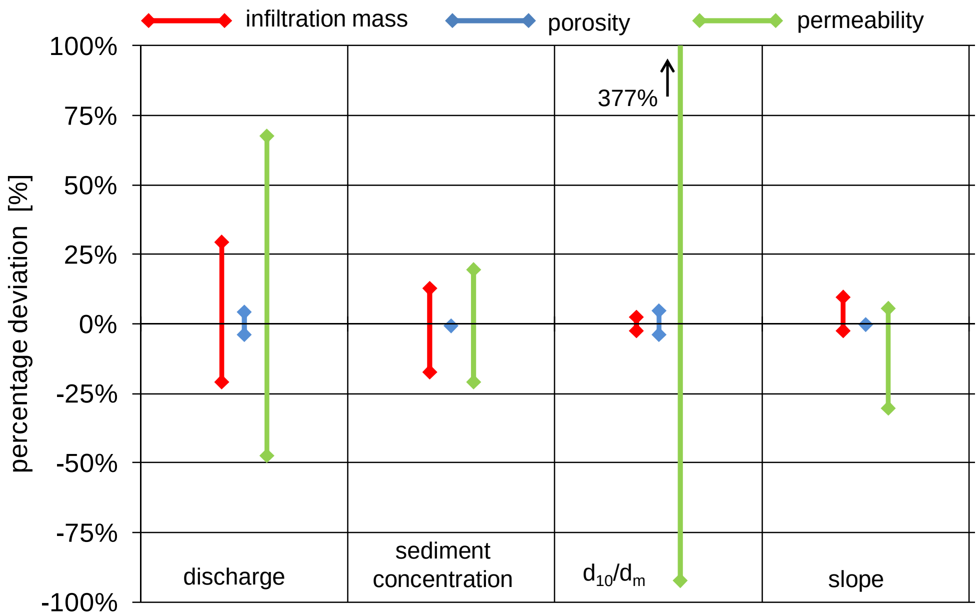


Figure D.1.8: Summarized results of the sensitivity analysis for input parameters with effects on infiltration masses, porosities and permeabilities

The main purpose of the sensitivity analysis of input parameters is to estimate the influence of uncertainties (e.g. measurement accuracy) on the investigated parameters infiltration mass, porosity, and permeability. Fig.D.1.8 illustrates that the largest effects on infiltration masses occur for varying discharges (50 %) and sediment concentrations (30 %), while the effects of the ratio d_{10}/d_m (5 %) and slope (12 %) are considerably smaller. Regarding porosity, the influence of sediment concentration (2 %) and slope (0.4 %) are noticeably smaller compared to discharge and d_{10}/d_m that show higher deviations from the calibration value (8 %). Comparable to the sensitivity analysis of the model-specific factors, the effects on permeability are significantly higher. The ratio of d_{10}/d_m has a detrimental impact on permeability although the influence of sediment infiltration is low. This is caused through the reduction of fine particles that creates a higher ratio of d_{10}/d_m, which leads to a generally coarser particle size distribution with higher values of porosity and subsequently to high values of permeability.

Comparing the results obtained from both sensitivity analyses it can be stated that for the chosen parameter ranges the model-specific calibration factors have a greater influence on sediment infiltration masses compared to the input parameter. However the uncertainty of input parameters, especially for discharge and sediment concentrations may lead to simulation errors for infiltration masses up to 50 % while for permeability the errors may be even more drastic. Given the strong influences of the calibration factors the uncertainty of measured input parameters may be compensated through the calibration process.

D.1.3 Conclusions of the numerical simulation in the flume

The numerical simulations of the laboratory experiments of Schaelchli (1993) are an important step to test the capability of SSIIM2 in simulating the highly dynamic sediment infiltration processes with its consequential impacts on porosity and permeability which are important habitat variables during the reproduction of gravel-spawning fish. The central conclusions obtained from these numerical simulations of the laboratory flume are listed below.

The calibration process of the numerical model SSIIM2 for simulating sediment infiltration processes contains several assumptions and restrictions. The first restriction is given to the assumption that sediment infiltration occurs only in the surface layer. This assumption differs from the observations made by Schaelchli (1993) who assumed the deposited particles between the surface and subsurface layer with an unhindered transport of infiltrating sediment through the coarse surface layer. This is approximated by defining the surface layer thickness according to the expected depth of sediment infiltration (Eq.C.1.10). The second assumption contains the initial particle size distribution at the beginning of each infiltration experiment as no data about the initial flushing to create an armoured layer was available. Therefore the approach of Guenter (1971) is used to calculate the armoured layer based on the subsurface particle size distribution. The final assumption addresses the unknown sediment-fluxes of the added suspended load which is assumed to consist of one particle size which is not present in the bed material and must be found through calibration.

The above mentioned assumptions and the calibration of SSIIM2 involving the exponent of the hiding/exposure function of Wu et al. (2000) as major calibration factor yields satisfying results with reasonable reductions of porosity and permeability as important habitat variables for the reproduction of gravel-spawning fish. However, the correlation (R^2=0.84) between the exponent of the hiding/exposure function and the infiltration resistance which is included in the semi-empirical approach of Schaelchli (1993) but not in the numerical model SSIIM2, is moderate. This indicates that the calculated infiltration resistance cannot fully be reproduced using solely the hiding/exposure exponent as calibration factor, although the correlation shows a clear trend of decreasing exponents of the hiding/exposure function with increasing infiltration resistances. Another restriction concerns the interstitial sediment transport (bed filtration, Chapter A.2.3.3) which is not implemented in both the semi-empirical and the numerical approach.

The two sensitivity analyses regarding model-specific parameters and input parameters are performed to test the influence of other potential calibration parameters of SSIIM2 as well as to estimate the uncertainty of input parameters with the objective to allow a more robust estimation of the numerical results. Both sensitivity analyses indicate in the predefined parameter ranges strong influences on the numerical simulation results. The model-specific parameters (settling velocity, active layer thickness, and exponent hiding/exposure) as potential calibration factors give significant deviations from the calibrated infiltration masses (up to 75 %) demonstrating the wide area of calibration opportunities. The input parameters show generally lower but still high degrees of influence, ranging from 50 % for discharge and 30 % for sediment concentrations, while the influence is 12 % for slope and 5 % for the ratio of d_{10}/d_m. These uncertainties of input parameters might be compensated through the strong effects of model-specific factors during the calibration process. In addition to the impact on infiltration masses the influences on porosity and permeability as important habitat variables are investigated. Of all model variables highest deviations were found regarding the permeability. This is expected, since even slight changes of porosity and d_{10} produce enormous variations of permeability (according to the Kozeny-Carman equation Eq.C.1.12). Although the results of the sensitivity analyses help to appraise simulated infiltration masses in terms of model calibration and uncertainty of input parameters, the gained insights of the sensitivity analyses are also determined by the predefined ranges of the investigated parameters.

Regarding the requirements on numerical modelling – as formulated in hypothesis 1 – the successful numerical reproduction of infiltration processes in SSIIM2 with the previously mentioned restrictions constitutes a key aspect in considering morphodynamic processes in habitat modelling. The resulting variations of porosity and permeability allow further analyses to estimate the suitability of the interstitial habitat (see Chapter C.1.3). It is important to note that the obtained simulation results are also subject to the strong influence of calibration factors. Therefore a thorough calibration has to be performed with calibration values that are within a range of physical meanings.

D.2 Case Study: River Spoel

The case study on the River Spoel in Switzerland includes the application of the entire multi-step habitat modelling framework presented in part C. The Spoel has been subject to numerous research programs for over 10 years with the primary goal to examine the effects of artificial floods on river ecology, especially with regards to the self-reproducing population of brown trout (*Salmo trutta*). Based on this experience, and the opportunity to take measurements directly before and after flood events, the Spoel is an appropriate study site to test the modelling framework considering both artificial flooding and low flow periods during the reproduction period to simulate the availability and quality of reproductive habitats for gravel-spawning fish. This chapter provides information covering the abiotic and biotic monitoring, the simulation of hydromorphological and hyporheic variability, and their effects on life-stages during the reproduction period of brown trout.

D.2.1 Study site description

D.2.1.1 Geographical situation

The catchment area of the River Spoel (295 km²) is located in the Central Alps of Switzerland and Italy of which more than 80 % is covered by the Swiss National Park (Scheurer & Molinari, 2003). The Park includes the Upper Spoel, where the study site is located, between the reservoir Lago di Livigno and Ova Spin. Today, the park includes a total area of 170.3 km² with an altitude ranging from 1400 m.a.s.l. to 3174 m.a.s.l., encompassing areas of subalpine and alpine levels. Fig.D.2.1 provides an overview of the study area and the investigated study site.

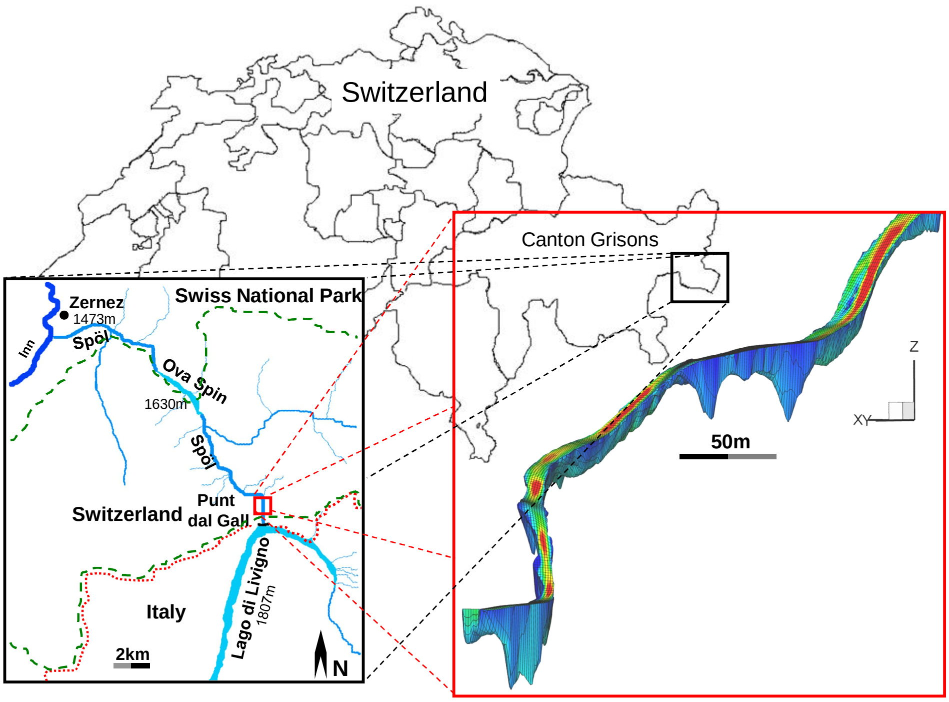


Figure D.2.1: Study site location: The Swiss National Park with River Spoel in the Alps of Engadin, Switzerland

According to the Categorisation System of the International Union for the Conservation of Nature (IUCN) the Swiss National Park belongs to the premier category (Category 1A), which are strictly protected areas in terms of biodiversity and geological/geomorphological features and have strict limitations with regards to human visitation, use and impact. The construction of the dam Punt dal Gall (Lago di Livigno) and Ova Spin (reservoir Ova Spin), and the corresponding water use (since 1970) of the River Spoel are considered in the contract of the National Park (Muerle, 2000). From Lago di Livigno the Upper Spoel flows 5.5 km through a canyon-confined valley before entering the Ova Spin reservoir. After 3.0 km the river crosses the alluvial plain of Zernez and finally joins into the River Inn after another 2.5 km. The study site itself is located between the two reservoirs, approximately 1 km downstream of Punt dal Gall and is directly affected from the reduced flow regulation downstream of the dam. The study site has a length of approximately 400 m with an average width of 15 m and a slope of 1.8 %.

D.2.1.2 Climate and hydrology

The study area is located in a meteorologically protected area due to the high mountain range of Bernina in the Southwest, the Silvretta in the North and the mountain Ortler in the South-east. This mountainous ring prevents the access of moist air resulting in a continental climate with high seasonal and daily variations in temperature with relatively low precipitation (Doering, 2002). Given to the mean altitude (2390 m.a.s.l.) and the percentage of glaciers (5.6 km², 1.9%) the hydrological regime can be assigned to the nivo-glaciaire regime type which is characterized by high flows in summer and low flows in winter. The Pardé-Coefficient before regulation (1951 - 1968) was in winter <0.5 and in summer >>1. Highest discharges occurred in June (Muerle, 2000) indicating that the major driver for floods is the snowmelt. Before regulation the mean annual flow ranged between 6.6 m³/s and 12.2 m³/s and annual flood peaks occurred regularly between 20 m³/s and 143 m³/s mostly during summer and early autumn (Robinson & Uehlinger 2008). Presently – due to both dams – a regulated flow of 1.44 m³/s in summer and 0.55 m³/s in winter is established. Fig.D.2.2 presents an overview of the hydrological regimes before and after regulation.

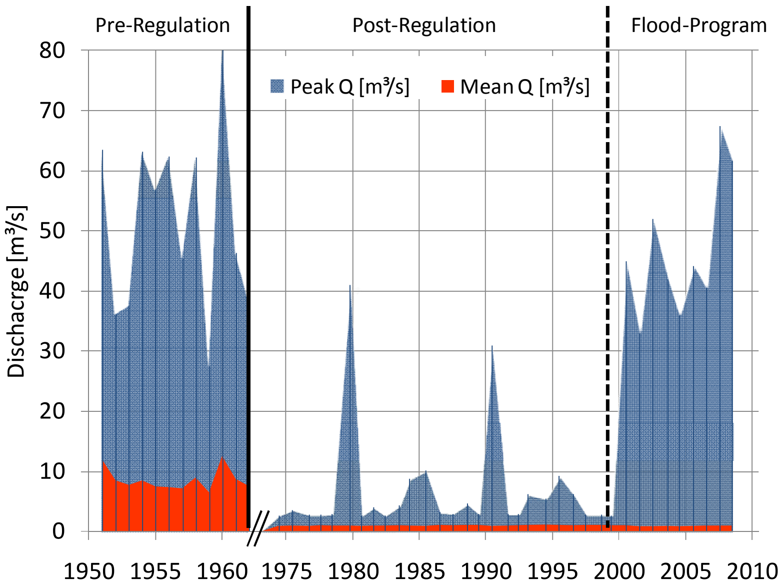


Figure D.2.2: Annual mean and peak flow from 1951 to 2008 in River Spoel at the gauge station Punt dal Gall

Based on environmental studies, completed in 1990, a three-year experimental flood program started in 2000 with the objective to determine the most optimal flood regime in terms of duration, magnitude and frequency to restore the hydromorphological heterogeneity of the river and to increase aquatic biodiversity. The objectives were to flush out accumulated fine sediments, reduce the dense coverage of mosses, and provide nutrients from the water release of the Livigno reservoir for the riverine fauna (Scheurer & Molinari, 2003; Muerle et al., 2003). In 2003 a series of papers were published in the Journal of Aquatic Sciences discussing the changes in river ecology due to the experimental flood program (Uehlinger et al., 2003; Robinson et al., 2003; Jakob et al., 2003; Ortlepp & Muerle, 2003).

D.2.1.3 Geology and morphology

As the River Spoel belongs to the upper and lower east Alps (Doessegger, 1987), the main sediment source of the river originates from dolomitic and calcareous scree due to the high gradient rocky side slopes of the valley (Truempy et al. 1997). The valley itself consists of a thin layer of Vallatscha dolomite covering the bedrock in the canyon. Significant alluvial quartary erosion fans and parts of old moraines consisting mainly of dolomite and limestone appear in the planal reach of River Spoel (Jakob, 2001). Typical for mountainous river reaches, the study site is characterised by a very heterogeneous particle size distribution ranging from clay and silt to large blocks. Even rocky material is found in the river bed indicating that the maximum of erosion depth has been reached in certain areas. The d_{50} for the study site ranges from 19 mm to 110 mm in the surface layer and from 9 mm to 40 mm in the subsurface layer (Muerle, 2000). Due to the construction of the reservoirs, the River Spoel has lost its mountainous character with its natural regularly occurring morphodynamic processes like bed alteration, lateral erosion from alluvial fans, and sediment mixing processes. During the regulated flow regime the sediment input is close to zero except of fine material that is introduced laterally during precipitation events or snow melt. Moreover the transport capacity is too low to transport incoming fine sediment further downstream leading to a substantial accumulation of fines, clogging the interstitials of the river bed. The images in Fig.D.2.3 give an impression of the study site in River Spoel.

Figure D.2.3: Images of the study-site in River Spoel showing the mountainous character and heterogeneous particle size distribution

D.2.1.4 Brown trout population

The loss of regulated floods - due to river regulation – has altered habitat conditions in the River Spoel drastically. The regulated flow regime in the River Spoel has mainly affected river morphology, sediment structure and food resources (Scheuer & Molinari, 2003). The flood pulse program aimed to improve the situation of the fish population of brown trout (*Salmo trutta*), that is the only fish species that lives and reproduces in the River Spoel

(Ortlepp & Muerle 2003). The brown trout population is isolated between the reservoirs Livigno and Ova Spin and genetic exchange with those of the River Inn is only possible downstream of the Ova Spin reservoir. As recreational fishing is restricted to only a short distance downstream of Ova Spin and as the last stocking occurred in 1993 below Livigno Reservoir the current status of the brown trout population can be stated to be natural. Given to the regulated flow a dense coverage of mosses developed in the River Spoel along with an increasing abundance of macroinvertebrates enhancing the food supply for fish leading to improved conditions factors (>1.0, Fulton Condition Index, Ortlepp & Muerle, 2003). Although food resources have increased, the loss of floods has led to a drastic reduction of the potential reproductive habitats in the River Spoel. The typically loose substrates in alpine rivers that allow fish to excavate spawning redds and provide sufficient oxygen supply of eggs was clogged and covered by fines in the River Spoel (Muerle 2000). The positive effect of the flood program to enhance the morphological situation is reflected in the number of spawning redds that have increased nearly three-fold since 2000. Similarly, repeated electro-fishing results prove a continuing fish population (Ortlepp & Muerle 2003).

D.2.2 Abiotic and biotic monitoring

The monitoring to investigate the effects of interstitial sediment dynamics on the reproduction of brown trout includes all required parameters that describe the changing habitat conditions from spawning to emergence. The monitoring is subdivided into abiotic monitoring including factors to describe the habitat environment during reproduction and biotic monitoring including the biotic response to changing abiotic conditions in form of survival rates during reproduction. Fig.D.2.4 provides an overview of the instrumentation in the study site which is elucidated in the following sections.

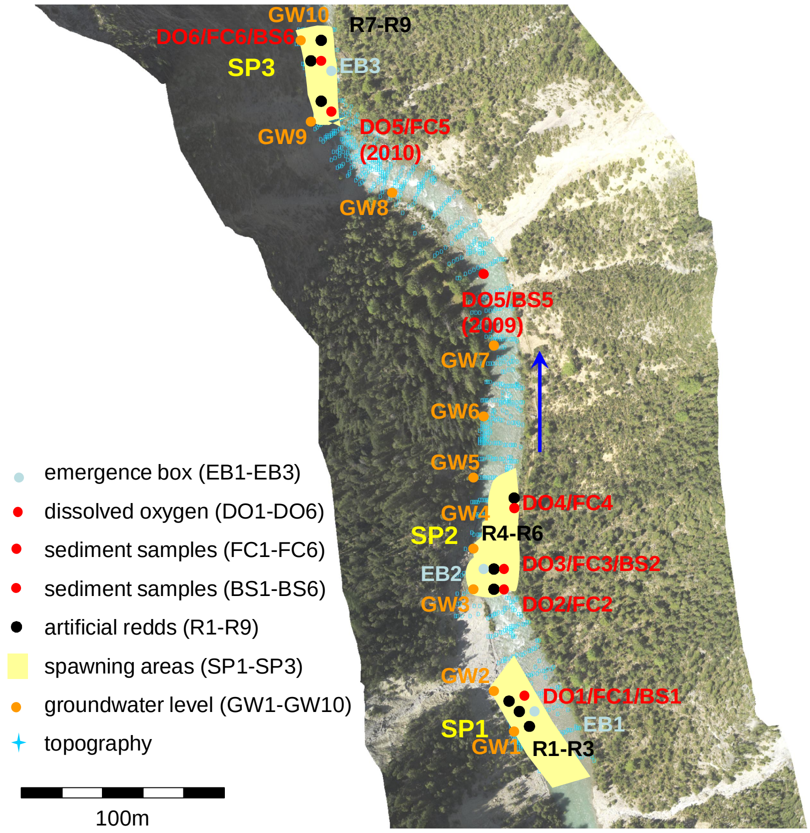


Figure D.2.4: Overview of spatial instrumentation during the monitoring period at the study site in River Spoel

The monitoring started in September 2009 and ended in May 2011. This period contains two artificial flood pulses (September 2009, July 2010) with detailed measurements before and after each flooding and two reproduction periods of brown trout. Appendix 4.1 gives a complete temporal overview of the abiotic and biotic monitoring.

D.2.2.1 Abiotic monitoring

Topography

The topography was measured one day before and one day after artificial flooding in 2009 and 2010 using a total station (Leica TPS 1205). Therefore, the measured bed level changes can directly be assigned to the flood events. Between the artificial flood events no bed alterations are assumed given to flow regulation. Approximately 2000 points were measured during each campaign to reflect the heterogeneous river geometry of the River Spoel. Based on the measured topography digital terrain models (DTM) are generated to provide input and calibration data for numerical modelling. In Appendix 4.4 examples of the DTMs of 2009 and 2010 before artificial flooding are shown.

Hydrologic and hydraulic data

Discharge

While the discharge data for the artificial floods in 2009 and 2010 was directly obtained from the Engadine Power Company (EKW) with a time interval of 15 minutes, the daily discharges during flow regulation were obtained by the gauge station Punt dal Gall (operated by the Swiss Federal Office for the Environment, FOEN), which is located approximately 400 m upstream of the study site. Both artificial floods have a magnitude of 40 m^3/s but timing before the reproduction periods is different. The flooding in 2009 occurred on 09/04/2009, while the flood in 2010 occurred on 07/01/2010. The regulated flow period with a discharge of 1.44 m^3/s ranged in both years until the beginning of October followed by another flow regulation of 0.68 m^3/s until mid-May. The hydrographs of the artificial floods as well as the entire daily based hydrograph encompassing the monitoring period from 09/02/2009 to 05/21/2011 are shown in Appendix 4.2.

Water levels

Distributed measurements of water levels were carried out for each topographical measurement campaign using the total station. Approximately 70 values distributed in each characteristic flow area were recorded for each topography and discharge to provide data for hydraulic calibration. Additionally, water levels were recorded during artificial flooding in 15 minute intervals to obtain information about the downstream boundary conditions.

Groundwater levels

To get an idea of the up- and downwelling processes of the study site, ten measurements of groundwater levels were conducted on 09/29/2010 to determine the differences in the surface water levels which indicate a positive or negative direction of the vertical hydraulic gradient. Groundwater levels were obtained by drilling holes at the banks with subsequent measurements of the groundwater level using the total station. The horizontal distance from the various boreholes to the river varied between 2.0 m and 0.5 m. Based on these measurements, two upwelling areas at the end of riffles are identified with a maximum absolute difference of 0.07 m and three downwelling areas with a maximum absolute difference of 0.11 m. The measured groundwater levels are interpolated laterally and longitudinally to obtain the spatial distribution covering the entire study site. Although this very simplified and imprecise technique does not provide detailed information about exchange processes between groundwater and surface water, it allows for a first identification of up- and downwelling areas. A map showing the spatial distribution of the differences between groundwater and surface water is shown in Appendix 4.4.

Interstitial temperature

Interstitial temperature data was provided by the Swiss Federal Institute of Aquatic Science and Technology (EAWAG, Robertson 2011) using one temperature data logger. Although the data logger was installed in the water column and not buried in the interstitials the data are useable as comparable temperature measurements in the interstitials during the sampling of dissolved oxygen concentrations between 10 cm and 20 cm depths show almost no vertical temperature variations. The data logger was located approximately 1200 m downstream of the study site and it is assumed that no relevant temperature changes occurs in-between. The temperature data interval was 1 hour and encompassed the total monitoring period from 09/02/2009 to 05/21/2011. The time-series of water temperature is shown in Appendix 4.3.

Sediment sampling

Monitoring method

Up to now, it has been widely accepted that the most accurate method to take sediment samples in rivers is freeze-coring. Therefore this method was favoured in the River Spoel. However, the instrument was only available from May 2010. Thus, the first sediment probes were taken by bulk sampling on the dry gravel bars next to the spawning areas SP1-SP3. Bulk sampling directly next to spawning redds resulted in a severe loss of fine sediments and thus were not usable for further analyses. Although these samples were no longer useable, proper sediment samples are available before and after each artificial flooding as well as at the beginning and end of the reproduction period. From a spatial point of view, sediment samples (FC1-FC6) were taken from the spawning areas SP1-SP3. Thus, variations in sediment characteristics (e.g. due to sediment infiltration) could be determined temporally and spatially. Bulk sampling on the gravel bars was performed by extracting all particles of the upper 10 cm plus the following 10 cm separately in an area of approximately 30 cm x 30 cm using shovels. Thus, particle size distributions of the surface and subsurface layer were obtained. Freeze-coring was performed using standpipes with a length of 1.25 m and an inner diameter of 3.6 cm. The standpipe was driven 35 cm-50 cm into the riverbed next to spawning redds. For insulation a perforated cylinder connected to a 25 l DEWAR-container (filled with liquid nitrogen (N_2)) was inserted into the standpipe. Liquid nitrogen was poured slowly into the standpipe for an average of 30 min. The frozen cores were extracted using a tripod with winch traction. Directly after extraction, length and width were measured and photographs were taken of each side of the core. If existent, vertical stratifications of sediment structure were considered during packing of the sediment samples to allow separate sieving analyses in the laboratory. The particle size distributions were obtained after drying and sieving using the sieve openings listed in Tab.C.1.1.

Results

Data preparation

While for bulk sampling particle size distributions are obtained for the surface and subsurface layer it was challenging to obtain particle size distributions of the surface layer using the freeze-coring technique. During the monitoring campaigns in summer, the relatively high flow velocities and high water temperatures prevented a successful extraction of the upper sediment layers as this layer could not be frozen. The application of the approach of Guenter (1971) to calculate the particle size distribution of the surface layer based on the subsurface distribution resulted in too coarse particle size distributions in the surface layer, based on a comparison with single freeze-cores during winter campaigns, where small amounts of the surface layer could be successfully extracted. To obtain comparable particle size distributions for all sediment samples, it was decided to use the approach of Guenter (1971) with subsequent averaging of the subsurface material, which gave reliable particle size distribution for the surface sediment layer. Again, this procedure was verified with available particle size distribution of the surface layer obtained during winter campaigns.

General sediment characteristics

To provide information about general sediment characteristics Tab.D.2.1 shows values of a typical particle size analyses for all sediment samples taken from the River Spoel. The sediment data are given in minimum, mean and maximum values with corresponding standard deviations separated by surface and subsurface layer.

Table D.2.1: General sediment characteristics based on particle size analyses considering all sediment samples taken from the River Spoel

	surface layer				**subsurface layer**			
	min	mean	max	σ [mm]	min	mean	max	σ [mm]
d_g [mm]	23.3	31.8	36.8	3.8	7.6	17.0	42.1	6.2
d_m [mm]	39.9	44.3	47.5	2.7	23.4	34.0	52.9	8.5
SO [-]	2.0	2.4	3.3	0.4	2.2	4.7	10.5	1.6
d_{10} [mm]	2.8	7.1	9.9	2.2	0.2	2.4	13.3	2.3
d_{50} [mm]	37.3	41.5	44.3	2.4	13.6	23.8	47.3	7.9
d_{90} [mm]	76.2	88.9	99.4	8.0	53.6	82.4	109.1	20.3
$p_{<2mm}$ [%]	1.8	4.0	8.2	1.9	3.7	12.0	26.3	5.2

For the surface layer both the geometric mean diameter (d_g), as well as the mean grain size (d_m) show relatively little variation, with values ranging from 23.3 mm to 36.8 mm and 39.9 mm to 47.5 mm respectively. This does not fully reflect the sediment diversity in the study site and is explained by the fact that all sediment samples are taken in typical spawning areas and not in areas which are not used for spawning. A high variation is shown for the d_{90} which is reasonable as single large particles sizes can drastically affect the particle size distribution given to their high weight. The percentage of fine sediments in the surface layer varied between 1.8 % and 8.2 %. The subsurface layer is generally characterized by higher variations compared to the surface layer, with lower values for d_g and d_m as more fine sediments are included in the subsurface layer (e.g. d_{10}, $p_{<2mm}$ in Tab.D.2.1). This is confirmed by the sorting coefficient which in the subsurface layer is significantly higher when compared to the surface layer indicating less pore space as it is often observed in rivers with a regulated flow regime (Baker, et al., 2010; Kantoush, et al. 2010; Shin, et al. 2011).

The sediment samples are compared to sediment data obtained by Muerle (2000) who found higher values for d_{50} in the surface layer (71 mm) with a significantly higher standard deviation (33 mm). This might be explained by different sampling locations, especially in locations that are not preferred for spawning due to coarser sediments. The percentage of fine sediments less than 2 mm in the surface layer lies in a comparable range (1-13 %), and the subsurface characteristics are generally in a good agreement. Muerle (2000) found in the subsurface layer mean d_{50}-values of 19 mm and a range of $p_{<2mm}$ between 4 % and 20 %.

Artificial flooding

The analyses of the effects of artificial flooding on particle size distributions are based on four bulk samples (BS) in 2009 and five freeze-core samples (FC) in 2010. Fig.D.2.5 visualizes the cumulative particle size distributions before and after the artificial floods that took place in 2009 and 2010 respectively.

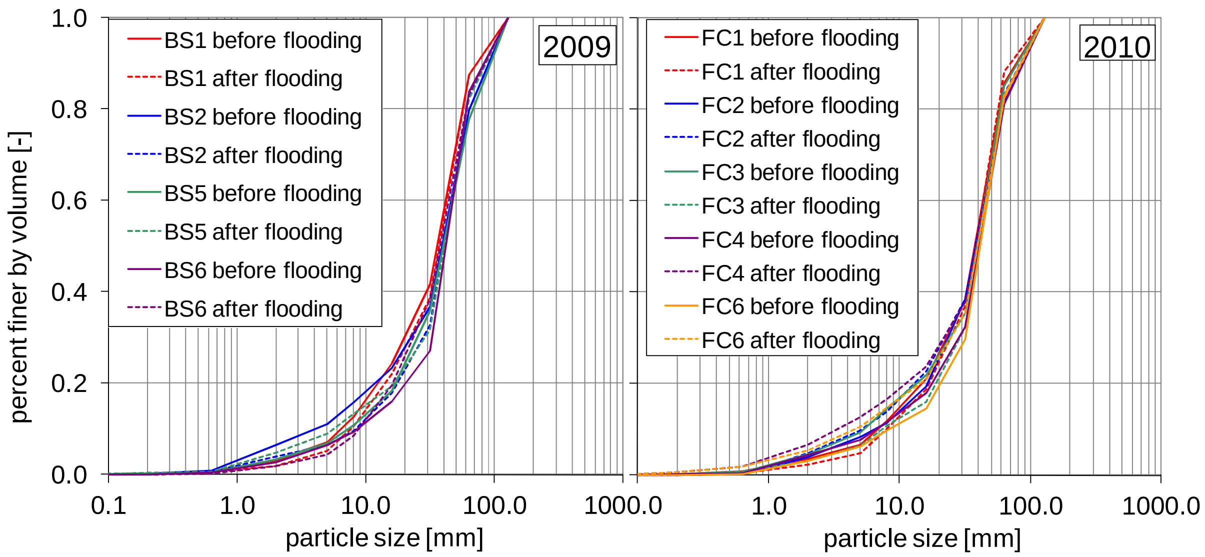


Figure D.2.5: Particle size distributions before and after artificial flooding in 2009 (bulk sampling) and 2010 (freeze-coring)

In 2009 all sediment samples after artificial flooding are characterised by a coarser particle size distribution, especially for particle sizes up to approximately 10 mm. The exception is BS5 which is marked by higher amounts of fine sediments compared to the situation before the artificial flood. The strongest decline of particles less than 2 mm was observed in BS2 from 6.5 % to 4.0 % (difference 2.5 %) followed by BS1 with a difference of 1.1 % and BS6 with a difference of 0.9 %. Although the amounts of fine sediments are not critical for reproduction before artificial flooding, the decline of particle sizes <2 mm in the surface layer proves the functionality of the artificial flooding. The effects of artificial flooding in 2010 differ from 2009. A decline of particle sizes <2 mm is only observed in FC1 and FC3, while FC2, FC4 and FC6 show rising amounts of particles <2 mm. The reductions in FC1 and FC3 are in the same order of magnitude as in 2009 with a value of 1.2% for FC1 and 1.4 % for FC3. However, FC2 shows an increase from 4.0 % to 4.8 %, FC4 an increase of 2.4 % and FC6 an increase between 3.0 % and 5.3 % of particle sizes < 2mm. Although the behaviour is different compared to 2009, the amount of fine sediments less than 2 mm does not reach the critical limit for spawning activities. The two different trends are reflected additionally in the sorting-index. While for 2009 the mean sorting-index decreases from 2.5 to 2.1 it is increasing for the artificial flood in 2009 from 2.4 to 2.6. The reasons for the differences in 2010 can only be speculatively drawn. One reason may be the amount of suspended loads which are coming through the outlet of the dam during flooding which were not quantified or the stepwise increase and decrease of flood pulses which were not performed in the flood 2009. In addition the number and extensions of participation events can differ between 2009 and 2010 leading to different lateral sediment-input to the River Spoel. An overview of characteristic particle size analyses of the surface layer before and after flooding (2009, 2010) is given in Appendix 4.5.

Sediment infiltration

To evaluate the variations of particle size distributions after artificial flooding through the end of the reproduction period, Fig.D.2.6 illustrates the infiltration masses and rates for both monitoring periods 2009/2010 and 2010/2011. In 2009, four bulk samplings at the beginning and four freeze-core samples are available to determine the infiltration masses while in 2010 six samples in total (all taken by freeze-coring) are available.

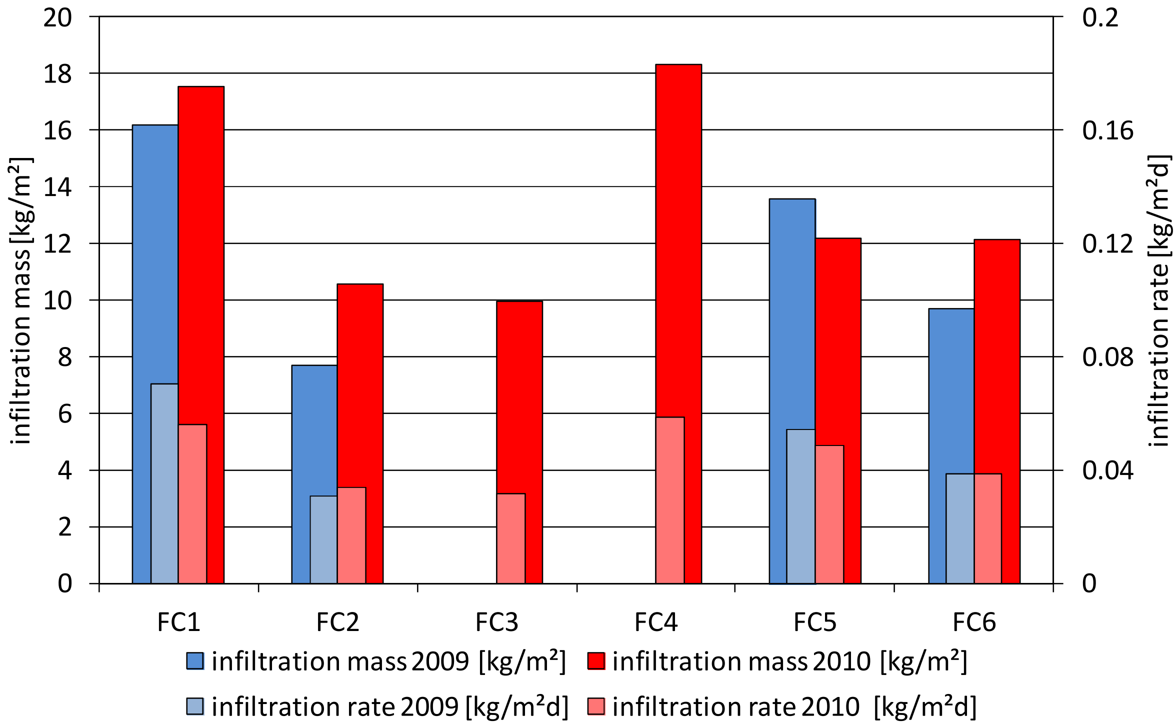


Figure D.2.6: Infiltration masses and infiltration rates during both monitoring periods 2009/2010, 2010/2011

For the monitoring period 2009/2010 the values of bulk sampling on 09/05/2009 are compared to the freeze-cores obtained on 05/12/05/2010 (250 days). To compare the amounts of infiltrated material the fractional percentages of particle sizes < 2mm are transformed in infiltration masses (kg/m²) considering additionally the different extensions of the infiltration areas (diameter of bulk samples and freeze cores). Highest infiltration mass is indicated for site FC1 with 16.2 kg/m² followed by FC5 with 13.6 kg/m². Lowest infiltration mass is indicated for FC2 with 7.6 kg/m² while FC6 is in-between with 9.7 kg/m². In 2010 the monitoring period lasted 313 days and only FC1, FC2, and FC6 can be compared to 2009 as FC3 and FC4 were only sampled in 2010, and the location of FC5 has since changed. A similar ranking to 2009 is observed for FC1, FC2, and FC6 while the total infiltration mass is higher for FC2 (10.6 kg/m²) and FC6 (12.1 kg/m²). This is mainly because of the longer monitoring period. To eliminate the effect of monitoring length the infiltration rates are calculated for a daily basis which are shown in Fig.D.2.6 in a lighter shade. Comparing the infiltration rates a reduction is indicated for FC1, while FC2 and FC6 have similar values in both monitoring periods. To check the reliability of the measured infiltration rates the data are compared to published data from Sear et al. (2008) who listed several infiltration rates in different rivers for base flows. The values range from 0.035 kg/m²d to 1.68 kg/m²d. According to Sear et al. (2008) this high variation results from different sampling techniques, monitoring periods and field-site conditions. However, the minimum of observed infiltration rate in the River Spoel is 0.031 kg/m²d, the maximum value is 0.071 kg/m²d and the mean infiltration rate is 0.046 kg/m²d. These observed infiltration rates are all close to the minimum value specified by Sear et al. (2008) which is trustworthy as the study site is located downstream of a dam with subsequently very low suspended loads. Characteristic particle size analyses of the surface layer at the beginning and end of each monitoring period for sediment infiltration (2009/2010, 2010/2011) as well as the particle size distributions are given in the Appendices 4.6-4.7.

Turbidity

Initially it was planned to install a turbidity meter to get a continuous time-series of suspended load concentrations based on a linear relationship between suspended load samples and turbidity measurements. However the turbidity meter was not available before July 2010 and it was not possible to achieve sufficient samples of suspended loads to develop a relationship between both parameters. Next to test measurements on 06/28/2010 and 07/01/2010, time-series of turbidity were available for the period from 08/25/2010 until 09/02/2010 and from 11/03/2010 to 12/15/2010. Several precipitation events occurred during these time-periods allowing an estimation how the suspended load concentrations change (relatively) in the event of precipitation. Appendix 4.8 presents the time-series of turbidity measurements.

Dissolved Oxygen (DO)

Monitoring method

For the in situ-measuring of dissolved oxygen (DO) in the hyporheic zone optodes (Klimant et al., 1995) was applied. The optode (Hach HQ20) was coupled using stationary devices similar to the method developed by Niepagenkemper & Meyer in 2002. The stationary measuring device consisted of two small steel pipes including a PVC-tube to suck interstitial water into a measuring cylinder where the optode is located. The perforated top of the steel pipe was lined with a 1.4 mm stainless steel net. The whole instrument was water- and airtight, so that no air or surface water could get into the measuring cylinder. This allowed repeated undisturbed sampling at the same sites over several months. To measure the absolute content of DO the interstitial water temperature was measured simultaneously. The steel pipes were installed in two different sediment depths (10 cm and 20 cm) in each spawning area that are similar to the natural depths of the buried eggs of brown trout (Chapter C.1.4.1) to obtain the vertical gradient of DO-concentrations.

In total 12 DO-probes were inserted on 12/11/2009 in the riverbed at six different locations (DO1-DO6) to determine the spatial distribution of DO-concentration. The DO measurements started in December 2009 and ended in May 2011 and were only removed during the artificial floods. Although temporal and spatial variation of DO-concentration are enormously high and continuous sampling is recommended (Malcolm et al., 2006), the sampling in monthly intervals was found to be the best ratio between effort and accuracy to measure the long-term effect of river regulation and the reduction in DO due to infiltration of fine sediments.

Fig.D.2.7 shows the steel pipes and the optode with the measuring cylinder and the syringe used to suck interstitial water.

Figure D.2.7: DO steel pipes with perforating tops and PVC-tubes used to suck interstitial water and measure the dissolved oxygen concentration in two sediment depths (10 cm, 20 cm)

Monitoring results

Fig.D.2.8 presents an example of the dissolved oxygen concentration at site DO5 for the entire monitoring period. Figured are the concentrations in the surface water as well as in the sediment depths of 10 cm and 20 cm. Additional information is given about the simultaneously measured interstitial temperature in Fig.D.2.8.

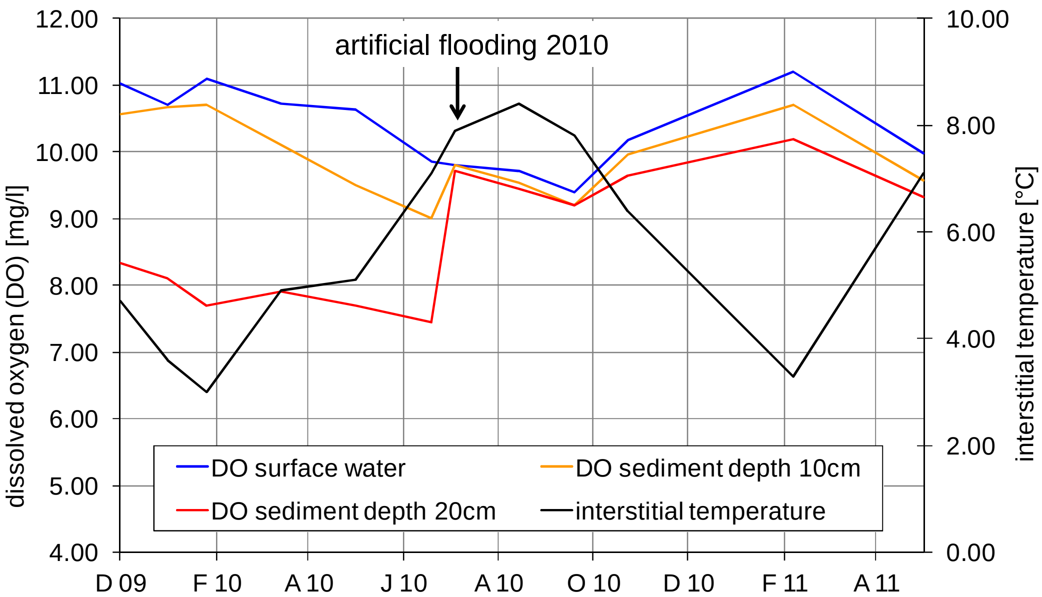


Figure D.2.8: Example dissolved oxygen concentration at DO5 for surface water, sediment depth 10 cm and 20 cm

The time-series of dissolved oxygen concentration in Fig.D.2.8 indicates an obvious vertical gradient at the beginning of the time-series, whereby the concentrations at the sediment depth of 10 cm are close to the ones of the surface water. Further, the influence of the artificial flood in July 2010 is clearly visible as the concentrations of both interstitial measurements approach the concentrations of the surface water. This indicates a renewal of the particle size distributions due to bed alterations with subsequently increasing interstitial oxygen concentrations in regards. The reverse behaviour of oxygen concentrations to the behaviour of interstitial temperatures reflects the solubility of dissolved oxygen concentrations at different temperatures. The minimum recorded oxygen concentration at a sediment depth of 20 cm is

7.45 mg/l, which may only have minor effects on the reproduction success. To provide information about spatial heterogeneity of measured DO-values, Tab.D.2.2 gives the minimum and maximum concentrations for DO1 to DO6 over the whole monitoring period.

Table D.2.2: Minimum and maximum concentration of measured dissolved oxygen concentration (DO1-DO6) over the whole monitoring period

		DO1 [mg/l]	DO2 [mg/l]	DO3 [mg/l]	DO4 [mg/l]	DO5 [mg/l]	DO6 [mg/l]
surface water	min	9.8	9.6	9.6	9.4	9.4	9.6
	max	11.1	11.2	11.1	11.2	11.2	11.5
sediment depth 10cm	min	9.8	7.0	8.7	5.3	9.0	9.2
	max	11.0	10.8	10.8	10.2	10.7	10.5
sediment depth 20cm	min	9.6	8.2	8.5	6.1	7.5	8.6
	max	10.8	10.0	10.8	9.3	10.2	10.2

For DO1, DO3 and DO6 all minimum values are above 8.5 mg/l which are not critical for the reproduction of brown trout considering the present interstitial temperatures. Tab.D.2.2 indicates lowest DO-concentrations for DO4 at a sediment depth of 10 cm with a value of 5.3 mg/l followed by DO2 with a value of 7.0 mg/l and DO5 with a value of 7.5 mg/l. A continuous vertical gradient is observed for DO1, DO3, DO5 and DO6 while for DO2 and DO4 lower concentrations are measured at a depth of 10 cm, these lower concentrations may be an indicator for a near surface colmation layer. The monitoring results of the temporal variations for all stations are figured in Appendix 4.9.

D.2.2.2 Biotic Monitoring

The biological monitoring comprises the mapping of spawning areas, the determination of the egg-to-fry (ETF) survival as well as the examination of emergence success. According to Dumas & Marty (2006) the egg-to-fry survival constitutes an important biological indicator for the quality of the stream habitat. Although the ETF-survival cannot be simulated exactly with the modelling framework given consideration only to abiotic factors, a comparison between the simulated reproduction habitat suitability and the ETF-survival could provide a rough performance criterion for the modelling framework.

Mapping of spawning redds

Since 1999 the spawning areas have been annually counted in the River Spoel by the local fishing authorities. The mapped distribution of spawning redds for the years 2009 and 2010 in the study site provides highly valuable information to calibrate the simulated habitat suitability for spawning within the modelling framework. Approximately an area of 10 m²-20 m² was chosen and both the test diggings as well as the final diggings of females were recorded separately. In 2009 the number of mapped redds in the study site was 43 while in 2010 it was slightly higher with 48 redds.

Artificial spawning redds

In the study site of the River Spoel three spawning areas (SP1, SP2, and SP3) could be identified according to the previously mapped spawning activities. They first site (SP1) is located upstream of a riffle while the second (SP2) and third (SP3) are both located downstream of a riffle (Fig.D.2.4). In each of these spawning grounds and in both spawning seasons (2009, 2010) three redds were buried artificially next to natural spawning redds. A pit, 10 cm to 15 cm deep and 15-40 cm wide was dug, filled with the surrounding gravels and finally extended upstream over a distance of 0.8 m – 1.5 m. During this operation the small particle sizes of the sediment mixture were carried downstream. This cleaning of fine sediments is similar to the natural digging of redds by female salmonids to ensure the sufficient oxygenation of the deposited eggs and developing larvae after hatching (Chapman, 1988; Meyer et al., 2008).

Survival from eyed-egg stage to hatching

Monitoring method

In this case study egg capsules were applied to determine the survival from the eyed-egg stage until hatching. The technique of inserting egg capsules in the substratum was firstly developed by Scrivener (1988) but it proved to be unsatisfactory, because of the size of capsules and insertion tube, which had to be hammered down through the gravel and thus disturbed the riverbed. Therefore a modified design of the miniaturized capsules of Dumas & Marty (2006) was constructed. The capsules were filled with 10 eggs separated by small gravels to avoid fungal contamination. The incubation capsules with a length of 9 cm and a diameter of 0.9 cm are cylindrical tubes made out of 1.4 mm mesh stainless steel netting that is able to retain hatched fry. The two ends of the cylinder were sealed by a plastic stopper equipped with an approximately 60 cm long nylon lines to find the capsules after hatching. Fig.D.2.9 shows the incubation capsules and how they are filled with eggs separated by sediments and inserted in artificial redds. In each artificial redd three incubation capsules were inserted to determine the survival rates until hatching.

Figure D.2.9: Egg capsules to investigate survival rates for the incubation period from eyed-egg stage to hatching

Monitoring results

The survival rates of hatched larvae were analysed for each capsule and averaged per redd and spawning area. For the season 2009-2010 the highest survival rates were observed in SP2 with a mean survival of 74 %, followed by SP3 with 72 % and SP1 with 71 %. The total mean survival rate for all spawning areas was 72 %. In the 2010-2011 season again the highest survival was observed in SP2 (70 %) but in SP1 (59 %) more hatched individuals were counted as in SP3 (55 %). Interestingly, all survival rates were considerably lower compared to the 2009-2010 season which might be explained by the timing of the artificial floods. However, during installation of the egg capsules in 2010 the poor weather conditions (-18 C) might have affected the survival rates already during egg handling. The results of all survival rates are listed in Appendix 4.10.

Emergence success

Method

To determine the success of emergence, box traps were installed in each spawning area, where the eggs can develop from the eyed-egg stage to the emergence stage into a box trap. The combined incubation and emergence box traps (Fig.D.2.10) were similar to those used by Dumas & Marty (2006). The incubation boxes were constructed of a 1.4 mm mesh with a length of 20 cm and a diameter of 12 cm. A second box was connected to the incubation box by a screwed lid that functions as a trap for the emerging larvae. Both cylindrical boxes were identical in design. The incubation boxes were totally filled with bed material and buried into the river bed, while the emergence boxes were only half-filled and located on top of the river bed. Before the incubation boxes were buried, 20-50 eggs were gently poured and distributed in the crevices. Lastly, the incubation boxes were connected to the emergence traps. In doing so the hatched larvae could emerge from the gravel of the incubation box through an opening into the emergence trap. Fig.D.2.10 shows different photographs of the emergence box-traps during installation in the river bed.

Figure D.2.10: Combined incubation-emergence box-traps to investigate the success of emerging larvae

Results

The combined incubation-emergence-traps could not be analysed correctly as it was observed that the fry could escape through the gap between the mesh and cylinder. In only three of nine of nine cylinders emerged larvae could be found. Although, the survival rate from egg deposition to emergence can vary from 0 to 90% between redds in the same river (Pauwels & Haines, 1994), the counted numbers of emerged individuals were determined to be useless as it is not known how many escaped. Therefore it does not reflect the effect of changing abiotic conditions throughout the reproduction period.

D.2.3 Simulation of hydromorphological variability

This chapter primarily aims on hypothesis 1 by checking if SSIIM2 is capable of simulating the temporal and spatial variations of most relevant hydromorphological processes affecting the reproduction of gravel-spawning. This includes the simulation of morphodynamic processes invoked by artificial flooding (before the reproduction period) and the simulation of sediment infiltration processes for regulated flow conditions (during the reproduction period). Following a description of the grid generation, this chapter contains detailed information about the model setups, calibration and validation processes to ensure an adequate representation of the simulated abiotic habitat variables for the multi-step habitat modelling framework.

D.2.3.1 Grid generation

The initial computational grid has to cover all areas that can be wetted during a simulation. This area is discretized by 400 cells in the longitudinal direction, 40 cells in the lateral direction and 5 cells in the vertical direction leading to a total number of 80 000 cells. The grid is unstructured and adaptive which means that with rising water levels and newly wetted areas new grid cells are created based on river geometry, water depth and the initial grid. For a body-fitted grid a grid algorithm is chosen which uses hexahedral and tetrahedral cells to accurately reflect the river bed topography. The initial computational grid is the basis for all numerical computations in this case study. Appendix 5.1 shows the three-dimensional grid with visualized flow velocities.

D.2.3.2 Morphodynamic simulation of artificial flooding

The objective of simulating the artificial flooding is to determine the flood-induced effects on the hydromorphological characteristics of the study site and to investigate if the predefined goals of artificial flooding – bed alterations, new sorting of bed material, flushing of fine materials – can be achieved to provide suitable habitat conditions for the reproduction of brown trout. According to hypothesis 1 it is additionally tested if SSIIM2 is capable of reproducing bed alterations and sorting processes as they were monitored during the field surveys.

Model setup

<u>Initial conditions</u>

For morphodynamic modelling the initial particle size distribution is required for each cell of the computational grid and each sediment layer. Therefore the measured particle size distributions before artificial flooding are specified in representative areas to cover the whole study site. In 2009 the particle size distributions of the four bulk samples are used while in 2010 the distributions of six freeze core samples are applied to specify the spatial distribution of the surface layer. For the same areas the measured subsurface distributions are used for the spatial distribution of the subsurface layer. According to Eq.C.1.10 the surface layer is specified with a thickness of 0.15 m which corresponds to the mean calculated infiltration depths of all initial particle size distributions. The subsurface layer functions as a sediment storage and delivery component in cases of erosion and deposition and is specified with a thickness of 5.0 m. Additionally an initial water surface is defined as the simulation is run in a ‘cold start’ (no previously calculated flow field). The initial water surface is spatially interpolated using the measured water levels before artificial flooding during each monitoring period.

<u>Boundary conditions</u>

For the upstream boundary, the hydrographs – presented in Appendix 5.2 – are specified for artificial flooding in 2009 and 2010. Additionally, time-series of sediment fluxes for each particle size are defined. The particle size distribution of the sediment-fluxes are derived from sediment samples of the alluvial fans, while the total concentrations are based on measurement of sediment concentrations in 2001 performed by Jakob (2001). Given the dam upstream, the eroded material from the alluvial fans is the only sediment input into the river. The total sediment fluxes during artificial flooding are also shown in Appendix 5.2. At the downstream boundary varying water levels are defined according to the varying discharges while for sediment-transport no downstream boundary condition is defined.

Sediment-Transport

The present version of SSIIM2 allows only the combination of the equations of van Rijn (1984) to consider both suspended and bed load. All other implemented transport-formulas in SSIIM2 consider total load or are used for computing the bed or suspended load separately. The bed load equation of Wu et al. (2000) is applied to simulate the morphodynamics changes during artificial flooding. The settling velocities are specified according to the formula of Zhang (1961). The critical shear stress is computed using a constant Shield's number which is used together with the hiding/exposure function of Wu et al. (2000) for calibration. For the simulations a time-step of 3 seconds is used with 50 inner iterations. Appendix 5.4 gives an overview of the most relevant model specification.

Results

Hydrodynamic calibration/validation

The first step of simulating the hydromorphological variability is the calibration of the hydrodynamic variability. Therefore the water levels before and after artificial flooding are compared to measured ones. To adjust the simulated water levels the roughness (k_s-value) is modified. In order to assure the model functionality the calibrated roughness values based on the artificial flooding in 2009 are used for validation by applying them for the simulation of the artificial flooding in 2010. For the artificial flooding in 2009, satisfactory results were obtained with a constant roughness value of 0.30 m. This roughness lies in the min-max range of three times the d_{90} (min_{3d90} = 0.18 m, max_{3d90} = 0.37 m) which is a common estimation of roughness values. Fig.D.2.11 shows the simulated water levels versus the measured water levels before and after artificial flooding in 2009 and 2010 (using k_s = 0.30 m).

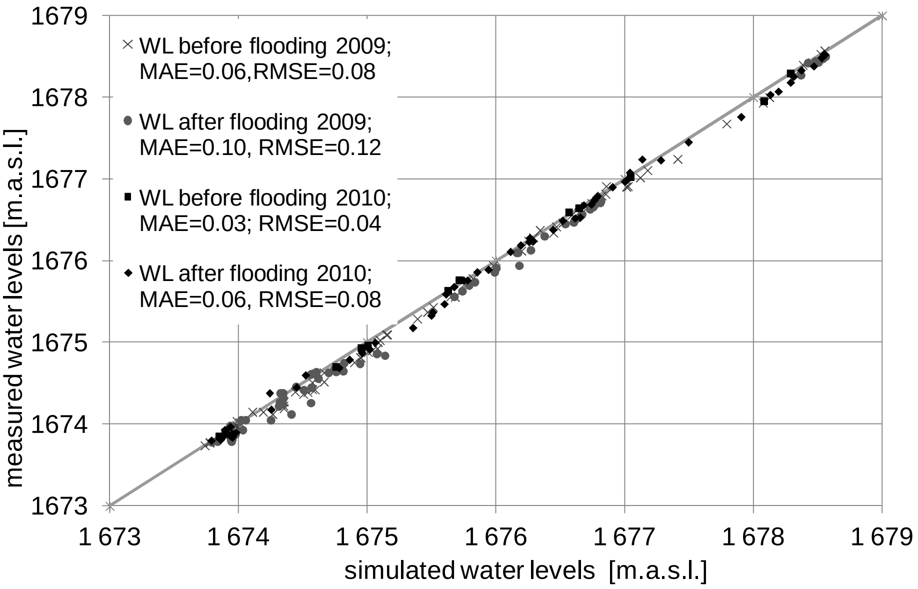


Figure D.2.11: Comparison of measured water level to simulated water level during the regulated flow period 2009 and 2010

The simulated water levels before flooding in 2009 show a mean absolute error (MAE) of 0.06 m and a root mean square error (RMSE) of 0.08 m. For the water levels after the flood the deviations are considerably higher with a MAE of 0.10 m and a RMSE of 0.12 m. However, the situation after flooding also includes the effects of simulated bed level changes which most probably lead to the higher deviations. Neglecting the water levels in the steep blocky rapids between SP1 and SP2 and upstream of SP3 result in an increasing performance before (MAE = 0.05 m, RMSE = 0.06 m) and after (MAE = 0.08 m, RMSE = 0.09 m) artificial flooding. The validation of hydrodynamic results for artificial flooding in 2010 proves the functionality of the numerical model with a MAE of 0.03 m before and 0.06 m after flooding. The corresponding RMSE are 0.04 m and 0.08 m respectively.

Following the direct differences between simulated and observed water levels, an analysis of the effect of artificial flooding on water levels is performed giving additional information about the spatial distribution of simulated and measured water levels which were carried out along the study site. Fig.D.2.12 visualizes the differences between measured water levels before and after artificial flooding in contrast to the differences of simulated water levels (artificial flooding in 2010).

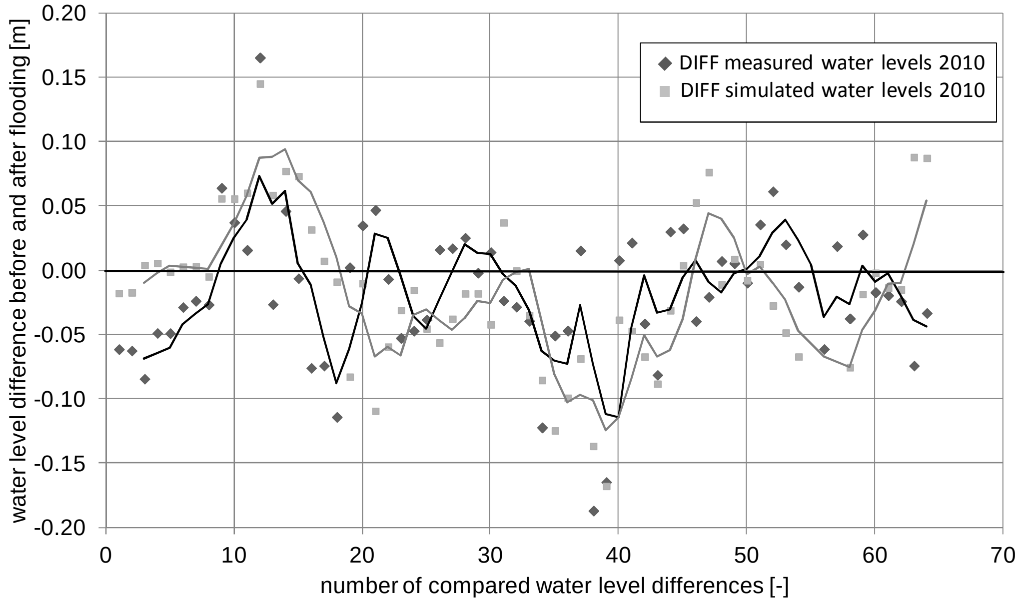


Figure D.2.12: Comparison of measured water level differences to simulated water level differences before and after artificial flooding in 2010

Fig.D.2.12 illustrates the effect of bed level changes on measured and simulated water levels along the study site. It is indicated by the figure that the general pattern of the measured differences is well approximated by the simulated differences. The maximum deviation is 0.16 m while the MAE is 0.04 m and the RMSE is 0.06 m. This evaluation gives a first look regarding the quality of the simulated bed level changes. Considering the extremely high geometric heterogeneity of the study site it can be stated that – based on these calibration and validation results – SSIIM2 is capable of simulating the effects of artificial flooding on hydraulic characteristics with sufficient accuracy. In parallel, the analysis of water level differences is performed for artificial flooding in 2009 (Appendix 5.3.).

Morphodynamic calibration/validation

To calibrate the morphological changes due to artificial flooding, the simulated bed level changes and particle size distributions are compared to measured values. In this case, the numerical model SSIIM2 is calibrated based on modifications of the exponent in the hiding/exposure function of Wu et al. (2000) and the Shields number. Correspondingly to the hydrodynamic calibration, the morphological variability is calibrated based on the artificial flood in 2009 while the obtained calibration factors are applied for the artificial flood in 2010 for validation.

Artificial flooding 2009 (calibration):

The calibration using the exponent in the hiding/exposure functions and the Shields parameter affect the resulting critical shear stress and thus, the beginning of sediment-transport. The exponent of the hiding/exposure function defines the probability of particles to be displaced while the Shields number is a dimensionless variable defining the critical shear stress for each particle size. Best results are obtained with an exponent of the hiding/exposure function of 0.3 and a Shields parameter of 0.065. The reduction of the recommended value of 0.6 (Wu et al., 2000) gives a limited hiding/exposure character, meaning that particles are easier set in motion compared to a value of 0.6. The Shields number of 0.065 leads to an opposite effect (compared to the recommended value of 0.047 (Meyer-Peter & Mueller, 1948)), increasing the critical shear stresses for each particle size. Using these two calibration factors it is found to control the morphological behaviour of the River Spoel during artificial flooding in an appropriate way. Fig.D.2.13 (A) shows the simulated and measured bed level changes induced by the artificial flood in 2009 while Fig.D.2.13 (B) presents a comparison of the relative frequency distributions of measured and simulated bed changes.

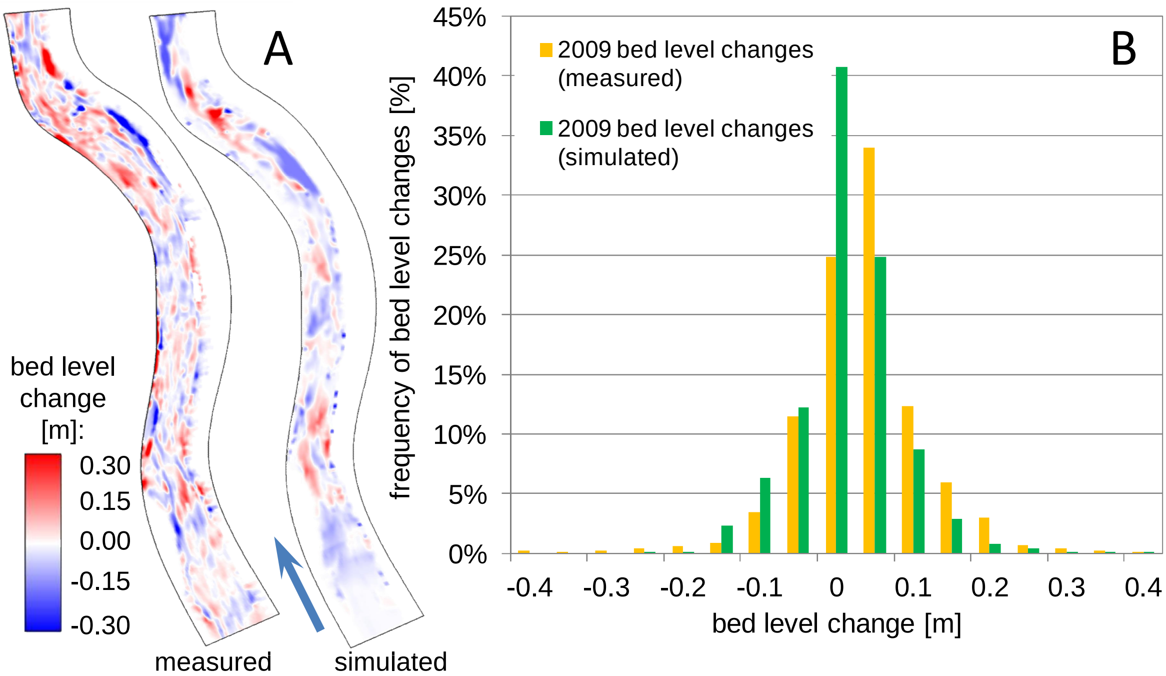


Figure D.2.13: Comparison of the spatial distribution of measured and simulated bed level changes due to artificial flooding in 2009 (A), and relative frequency distributions for measured and simulated bed level changes (B)

The spatial pattern of bed level changes due to artificial flooding in 2009 show higher bed deformations in the steep riffle areas downstream of SP1 and upstream of SP3 compared to the areas in-between, which is visible in both the measured and simulated bed level changes (Fig.D.2.13 A). Although some similar bed deformations are indicated, the spatial distribution of measured bed level changes cannot fully be reproduced by the numerical model SSIIM2. However, Fig.D.2.13 (A) indicates that the river bed is in motion leading to spatial redistribution and resorting of particles sizes which is the major purpose of the artificial floods. Moreover, the simulated bed deformations are of the same magnitude compared to the measured ones (Fig.D.2.13 B). The frequency distribution of measured bed level changes gives 98 % in the range of ± 0.30 m while the simulated bed level changes have 99 % in the same range. Most bed level changes are between -0.05 m and +0.05 m. For the measured bed level changes this includes 70 % while for the simulated ones it includes 77 %. Based on these values it can be concluded that the simulated bed deformations are of a moderate accuracy.

In addition to bed deformation, the resorting of particle sizes is of significant interest in terms of proper modelling. Therefore the measured particle size distributions (obtained by bulk sampling (BS1-BS6)) are compared to the simulated particle size distributions with SSIIM2. Fig.D.2.14 gives both the cumulative particle size distributions and the relative particle size distributions for measured and simulated values. Additionally, the initial measured particle size distribution is shown to visualize the effect of artificial flooding.

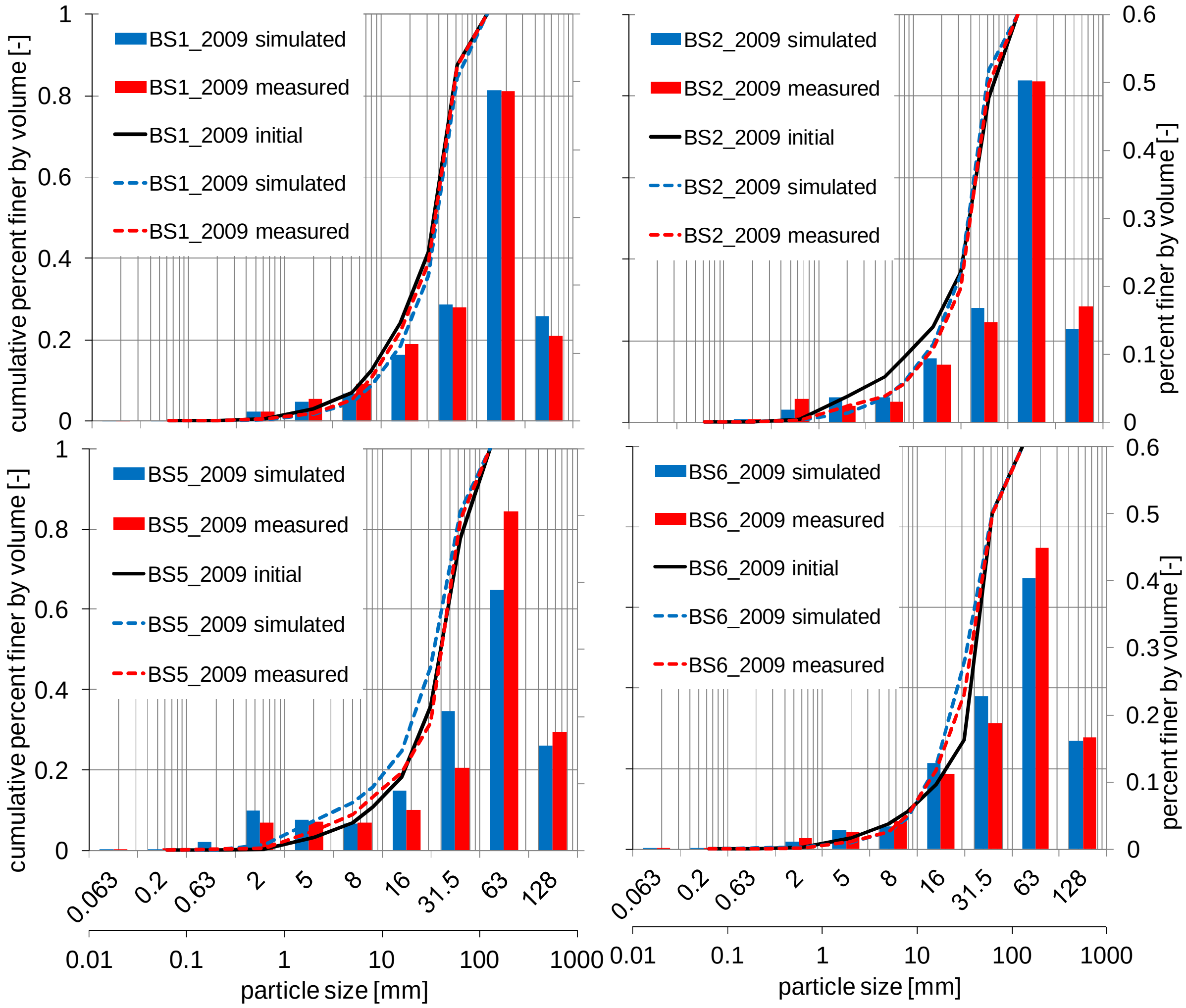


Figure D.2.14: Comparison of the measured and simulated particle size distributions after artificial flooding in 2009 including the initial measured particle size distribution before flooding (black line)

For the artificial flood in 2009, four sediment samples were available before and after flooding. The simulated values in Fig.D.2.14 are based on an average of the five closest cells to the measured location to ensure that not only a single spot fits to the measured values. Fig.D.2.14 indicates that the general effects of artificial flooding on particle size distributions are successfully reproduced by SSIIM2. Both the reduction of fine particle sizes in BS1 and BS2 as well as the increase of fine sediments in BS5 are well simulated by SSIIM2. A good performance is also identified for BS6 with a fractional decrease of fine sediments up to 8 mm and an increase of particles > 8mm. A comparison of typical particle size analyses for measured and simulated distributions for artificial flooding in 2009 is shown in the following table (Tab.D.2.3), while for the artificial flooding in 2010 it is shown in Appendix 5.5.

Table D.2.3: Comparison of typical particle size analyses for measured and simulated particle size distribution after artificial flooding in 2009

	BS1		BS2		BS5		BS6	
	meas	sim	meas	sim	meas	sim	meas	sim
d_g [mm]	29.6	32.7	33.8	31.5	31.9	25.5	30.6	32.3
d_{ch} [mm]	41.0	43.6	45.0	42.4	45.1	39.9	41.4	43.5
SO [-]	2.3	2.1	2.2	2.2	2.4	2.7	2.2	2.2
d_{10} [mm]	7.6	9.0	8.5	8.2	5.6	3.8	9.4	9.1
d_{50} [mm]	38.8	40.7	42.3	40.2	42.8	35.0	34.6	39.7
d_{90} [mm]	76.3	86.0	89.8	80.1	91.2	86.2	88.4	89.1
$p_{<2mm}$ [%]	1.9	1.8	3.9	2.4	4.7	7.3	1.6	1.8

Artificial flooding 2010 (validation):

For the artificial flood in 2010 the same calibration factors are applied to assure the functionality of SSIIM2 to reproduce the observed morphological changes for a different set of initial and boundary conditions. Fig.D.2.15 (A) presents the spatial pattern of simulated and measured bed deformations while Fig.D.2.15 (B) shows the relative frequency distributions of bed level changes.

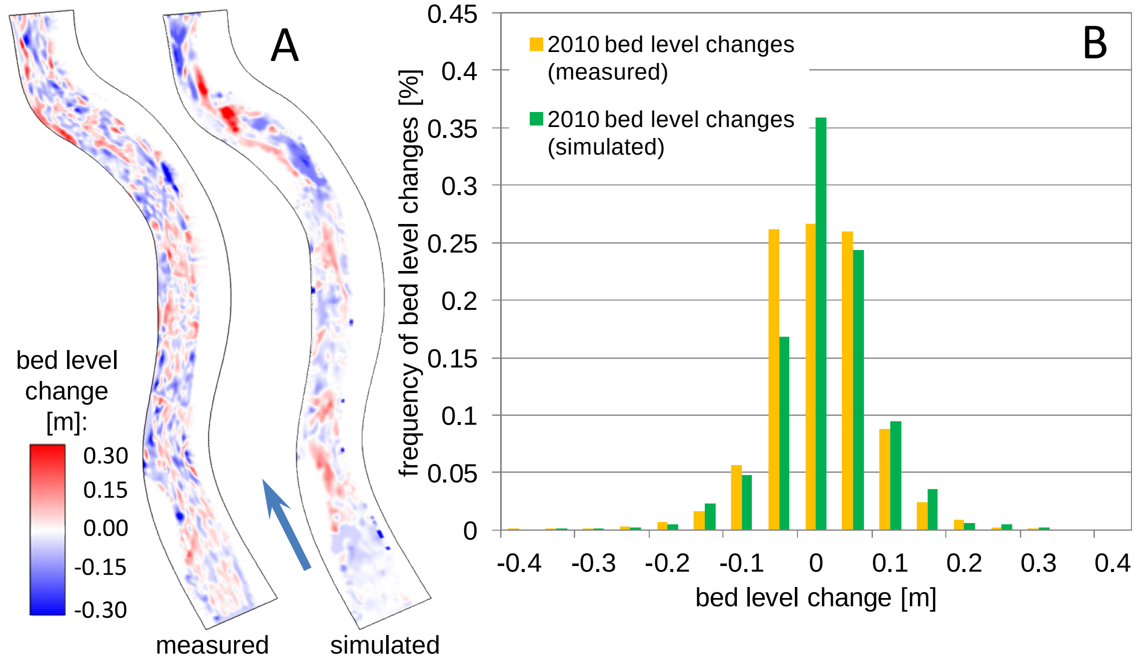


Figure D.2.15: Comparison of the spatial distribution of measured and simulated bed level changes due to artificial flooding in 2010 (A), and relative frequency distributions for measured and simulated bed level changes (B)

Similarly to artificial flooding in 2009 the bed level changes are in a range of ± 0.30 m (99 % for measured and simulated bed level changes) with the majority of bed deformation occurring in the range of ± 0.05 m (78 % for measured and 77 % for simulated bed level changes). This confirms the good performance of the calibrated model. However, Fig.D.2.15 (B) indicates nearly 10 % more erosion (class -0.05 m) for the measured values and the simulated values have 10% higher values in the class of no bed level changes. This behaviour can also be observed in the spatial visualization of Fig.D.2.15 (A) where significantly more erosion (blue) can be indicated for the measured values while for the simulated values wide areas with no bed level changes (white) are identified. However, also similar erosion and deposition patterns areas are recognized in Fig.D.2.15 (A), for instance up- and downstream of SP3 as well as in and downstream of SP2. Regarding the analysis of the measured and simulated particle size distribution for the artificial flooding in 2010, it can be stated that the redistribution and resorting due to artificial flooding are well approximated with SSIIM2. The different behaviour of the artificial flood in 2010 (compared to 2009, Chapter D.2.2.1) is accurately reproduced in SSIIM2 showing fractional reductions of fine sediments for FC1 and FC3, while for FC2, FC4, and FC6 a fractional increase is simulated. The validation result of the sorting processes regarding the particle size distributions is presented in Appendix 5.6.

Discussion about simulation of artificial flooding

This intermediate discussion aims to evaluate the results obtained from numerical modelling of artificial flooding in terms of reliability and uncertainty including the requirements on numerical modelling formulated in hypothesis 1. Lastly the simulations of the artificial flooding are analysed regarding their ecological significance.

Reliability and uncertainty

Uncertainties in simulating the morphological effects of artificial flooding arise from sediment sampling and the simplification of natural processes in the model specifications. Because of these simplifications the measured bed level changes have to be checked as to whether they are induced by artificial flooding or result from uncertainties during measuring topographical points with subsequent interpolation to a DTM. The uncertainty of DTM generation is tested by comparing the measured topography after artificial flooding in 2009 with the measured topography before the artificial flood in 2010. As only regulated flow conditions are between these two dates, no bed level changes are expected. The MAE in this case is 0.05 m while the MAE of bed level changes before and after artificial flooding is 0.10 m in 2009 and 0.09 m in 2010. This implies that only bed level changes higher than 0.05 m can accurately be assigned to artificial flooding. This result makes it difficult to evaluate the measured and simulated bed level changes in terms of reliability where more than 70 % of bed deformations lie in the range of ± 0.05 m. As the spatial pattern includes similar erosion and deposition areas and the simulated particle size distributions after flooding adequately reproduce the measured ones (for both calibration and validation), it can be concluded that the morphological changes in all probability are invoked by artificial flooding. However, for both artificial floods the measured bed deformations cannot fully be reproduced by SSIIM2. These discrepancies may also result from the insufficient spatial resolution of sediment samples that were taken only in spawning areas and do not reflect the whole sediment diversity in the river reach. Regarding the particle size distributions, SSIIM2 successfully reproduced the effects of artificial flooding as for all available sediment samples the measured fractional changes of particle sizes are well reflected by the numerical model. The obtained results confirm an important part of hypothesis 1, which requires the proper reproduction of hydromorphological changes relevant to the reproduction of gravel-spawning fish using numerical model tools. The second part concerning the accumulation of fine particles during low flow period is addressed in Chapter D.2.3.3.

Ecological significance

The aim of artificial flooding is primarily to improve and maintain ecological integrity by creating dynamic reproductive habitat patches as an important ecosystem function despite regulated flow (Scheurer et al., 2003). In terms of the reproduction of brown trout this implies regular bed alterations to create a renewal of substrate conditions (Merz et al., 2004, Chapter A.2.2.5) by breaking armoured layers and flushing fine sediments out of the interstitials of the riverbed. Fig.D.2.13 and Fig.D.2.15 confirm occurring bed level changes for both artificial floods in 2009 and 2010. The required bed alterations to break up the surface sediment layer are achieved in both years enabling the redistribution and resorting of particle sizes in horizontal, vertical and longitudinal direction. However, the major bed level changes are in the range of ± 0.05 cm which can be considered as an absolute minimum regarding the provision of suitable reproduction grounds for brown trout as typical egg burial depths are in the range of 0.02 m – 0.23 m (Chapter C.1.4.1). Nevertheless, analyses of particles size distribution after artificial flooding (Fig.D.2.14) indicate that the fractional percentages of sediments less than 2 mm in the surface layer (0.15 m) are not in a critical range for spawning purposes, although some sediment samples have shown an increase of fine sediments after artificial flooding. To test if the artificial floods are sufficient to meet the habitat requirements during the long reproduction period is one aspect addressed in the multi-step habitat modelling framework.

D.2.3.3 Morphodynamic simulation of sediment infiltration

Given the flow regulation over the whole reproduction period, sediments in suspension are able to infiltrate into the interstitials of the river bed affecting the interstitial habitat suitability by reducing the available pore spaces. This chapter aims to test the second part of hypothesis 1, if a numerical model is capable to simulate these infiltration processes in natural rivers. Therefore the results from the investigation of the laboratory flume are used (Chapter D.1) as well as the semi-empirically simulated infiltration masses (Schaelchli, 1993) to compare the obtained numerically simulated infiltration masses with SSIIM2. The following section provides information about the model setup, the calibration and validation processes. Again the calibration is performed for the low flow period in 2009/2010 while the period 2010/2011 is used for validation.

Model setup

Initial conditions

The initial conditions for simulating sediment infiltration processes are primarily based on the calibration/validation result of the previously performed simulations of artificial flooding in 2009 and 2010. The initial spatial particle size distributions and composition of the surface and subsurface layer correspond to the simulated ones after artificial flooding. Again the thickness of the surface layer is specified as 0.15 m according to Eq.C.1.10 while the subsurface layer is assigned a thickness of 5.0 m. The initial river bed geometries are based on the measured ones following artificial flooding to ensure a proper representation of the wetted areas and the resulting hydraulic forces.

Boundary conditions

The daily discharges obtained from the gauge station Punt dal Gall are applied for the upstream boundary condition. The simulation period 2009/2010 for calibration starts directly after the artificial flooding (09/05/2009) and ends at the end of the reproduction period on 05/12/2010 while the simulation period 2010/2011 (validation) starts accordingly on 07/02/2010 and ends on 05/10/2011. The definition of boundary conditions for sediment-transport was difficult as suspended load measurements during the low flow period could not successfully be performed and hence, no information about the sediment fluxes for each particle fraction, which are required by the numerical model SSIIM2, is available. Therefore several assumptions are made. The first one includes the specification of a constant sediment flux, which is probably not accurate for the River Spoel as the input of sediments during flow regulation is largely determined by precipitation events. The second assumes a certain distribution of this constant sediment flux over the range of particle sizes less than 2 mm, which are expected to be transported during flow regulation. Regarding the constant sediment flux it is referred to measurements performed by Jakob in 2001 who found an average value of 0.0048 kg/m³ while the distribution of this constant sediment flux over particle sizes is found by calibration. For the downstream boundary water levels according to the daily discharges are specified while for sediment-transport no boundary condition is required.

Sediment-Transport

Similarly to the simulations in the laboratory flume only the suspended load is computed using the equation of van Rijn (1984) plus the hiding/exposure function of Wu et al. (2000). The dimensionless Shields number is calculated based on an implemented parameterization of the Shields curve (Fig.A.2.2) while the settling velocities are computed using Zhangs formula (1961). Given to the relatively long simulation period (250 days in 2009 and 313 days in 2010) several test simulations were performed to get the maximum allowable time-step for proper modelling. The time-step was varied between 10 seconds and 1800 seconds and it was found that the simulation results obtained with a time-step of 900 seconds showed negligible differences to the results obtained with a time-step of 10 seconds. To obtain a numerically stable solution the inner iterations for the period 2009/2010 are specified with a number of 50 while for the 2010/2011 simulation period 200 inner iterations are specified. Appendix 6.2 provides information about all specified model parameters to simulate sediment infiltration processes with SSIIM2.

Results

Calibration of sediment infiltration using the semi-empirical approach of Schaelchli (1993)

In a first approach the equations of Schaelchli are applied using the numerical modelling of SSIIM2 to provide the required input parameters (Chapter C.1.2.1). No information is available regarding the seepage length to calculate the vertical hydraulic gradient based on the measured differences between groundwater and surface water. Therefore this parameter is used for calibration together with the empirical factor e_S as it is specified in Eq.B.2.9. The measured infiltration masses are based on the bulk samples obtained directly after the artificial flood in 2009 and the freeze-cores, sampled at the end of the reproduction period in 2010 (Chapter D.2.2.1). Unfortunately measured sediment samples are only available at the beginning and end of the investigated period. Consequently only the total infiltration mass can be evaluated but not the temporal progress of the sediment infiltration. However, based on the results of the laboratory flume experiment it is assumed that the approach of Schaelchli gives at least an approximation of the temporal progress of sediment infiltration processes.

Fig.D.2.16 gives the infiltration masses per square meter based on an average of the five closest cells to the freeze-core samples FC1, FC2, FC5, and FC6 considering three different seepage lengths (0.20 m, 0.30 m, and 0.40 m) to assess the influence of this variable (Fig.D.2.16 B). For the empirical factor e_S the value $1.2x10^{12}$ - as defined by Schaelchli

(1995) - was found to perform best. The left hand side of Fig.D.2.16 (A) gives the spatial distribution of sediment infiltration masses (m_k) at the end of the investigation period (with a seepage length of 0.30 m).

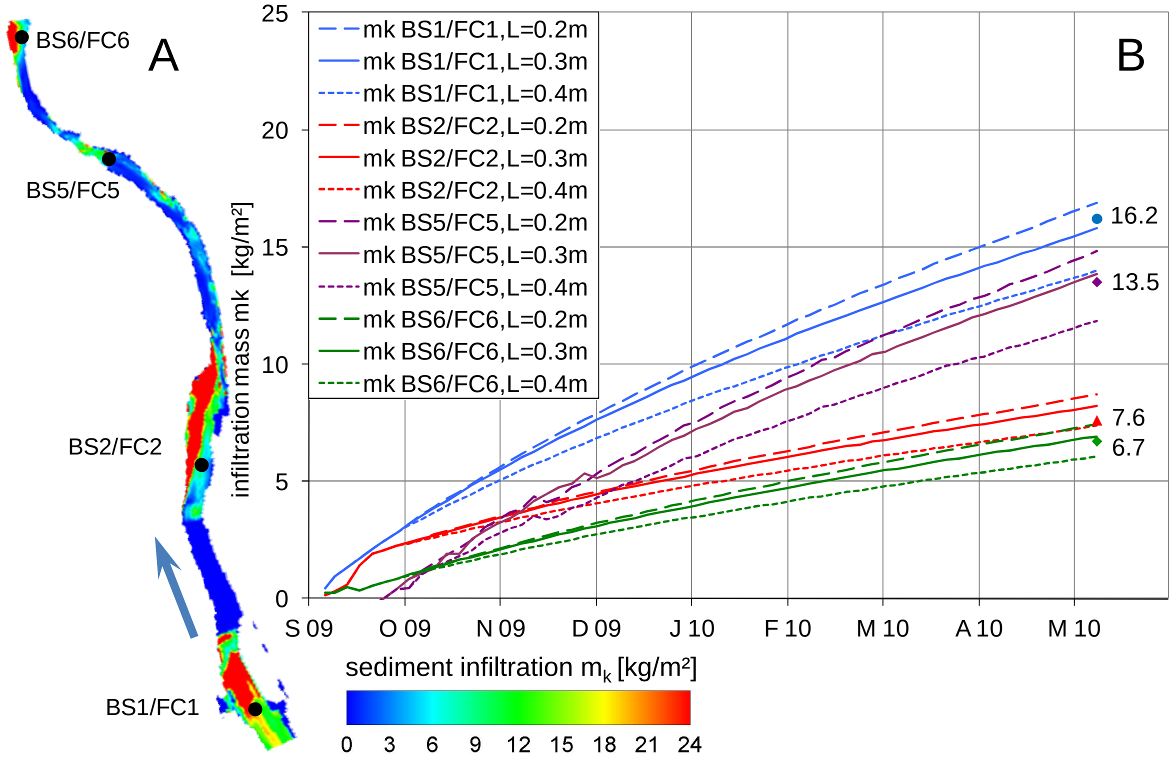


Figure D.2.16: Simulation of sediment infiltration using the semi-empirical approach of Schaelchli (1993). (A) gives the spatial distribution of sediment infiltration at the end of the infiltration period while (B) gives the temporal progress of sediment infiltration for different seepage lengths

In the visualization of the spatial distribution (Fig.D.2.16 A) sediment infiltration is mainly identified in all spawning areas (SP1-SP3) while in-between spawning areas low or no sediment infiltration is simulated. This is primarily given to the higher shear stresses in these regions, maintaining the transported particles in suspension and preventing a settling to the river bed. Fig.D.2.16 (A) shows the highest sediment infiltration for site BS1/FC1 followed by site BS5/FC5 which are both before riffles, where typically higher vertical hydraulic gradients are observed. BS2/FC2 and BS6/FC6 are downstream of riffles with lower sediment infiltration masses which are also simulated by the semi-empirical approach of Schaelchli. The temporal progress of sediment infiltration (Fig.D.2.16 B) for different seepage lengths shows a continuously rising infiltration for all sampled locations. The numbers in Fig.D.2.16 (B) give the measured sediment infiltration masses and indicate that simulations with a seepage length of 0.30 m (solid line) perform in a satisfying manner. Compared to the uncertainties during monitoring the influence of the seepage length can be regarded as low, as the maximum deviation is 2.9 kg/m² and the mean deviation is 2.3 kg/m².

Another important issue to be considered is the equilibrium between resuspension and deposition, indicating the limit for sediment infiltration processes. Therefore the maximum infiltration resistance and the subsequent minimum permeability based on Eq.B.2.11 and Eq.B.2.14 are computed and compared to the resulting minimum permeability using the approach of Schaelchli (Eq.B.2.13). The minimum permeability for all samples is below 12 cm/h while the resulting permeability values in the infiltration period are all above this critical value (Appendix 6.1). Hence no equilibrium between deposition and resuspension is achieved within the infiltration period.

Calibration of sediment infiltration processes using SSIIM2

For calibrating the sediment infiltration processes simulated with SSIIM2, the simulated infiltration masses per square meter [kg/m²] of particles less than 2 mm are compared to the measured ones (Chapter D.2.2.1). To calibrate the temporal progress of infiltration the numerically simulated infiltration masses are compared to the temporal infiltration behaviour of infiltration masses obtained by the semi-empirical approach of Schaelchli (1993).

The calibration process of SSIIM2 is primarily focused on the exponent of the hiding/exposure function in Wu et al. (2000) to adjust the equilibrium between deposition and resuspension considering the results obtained by numerical modelling of the sediment infiltration processes in the flume (Chapter D.1). Contrary to the particle size distributions of the bed material applied in the flume experiment, the particle size distributions in the River Spoel are characterized by a more heterogeneous distribution due to the mountainous character of River Spoel. This is illustrated by comparing the mean ratios of d_{10}/d_m of the surface layers which are 0.041 for the flume experiment and 0.16 for the River Spoel indicating low infiltration resistances. According to Fig.D.1.5 this implies subsequently an application of a relatively high exponent in the hiding/exposure function of Wu et al. (2000).

At first, simulations with varying exponents in the range of $0.6 \le m \le 0.9$ were performed leading to unsatisfying results as an equilibrium between incoming suspension loads and resuspended material is achieved resulting in no further depositions. According to Schaelchli's equations regarding the limiting state of sediment infiltration the equilibrium between deposition and resuspension does not occur in the considered infiltration period. Fig.D.2.17 illustrates the infiltration masses for these preliminary simulations at the location of the three artificial redds (R1-R3) in SP1.

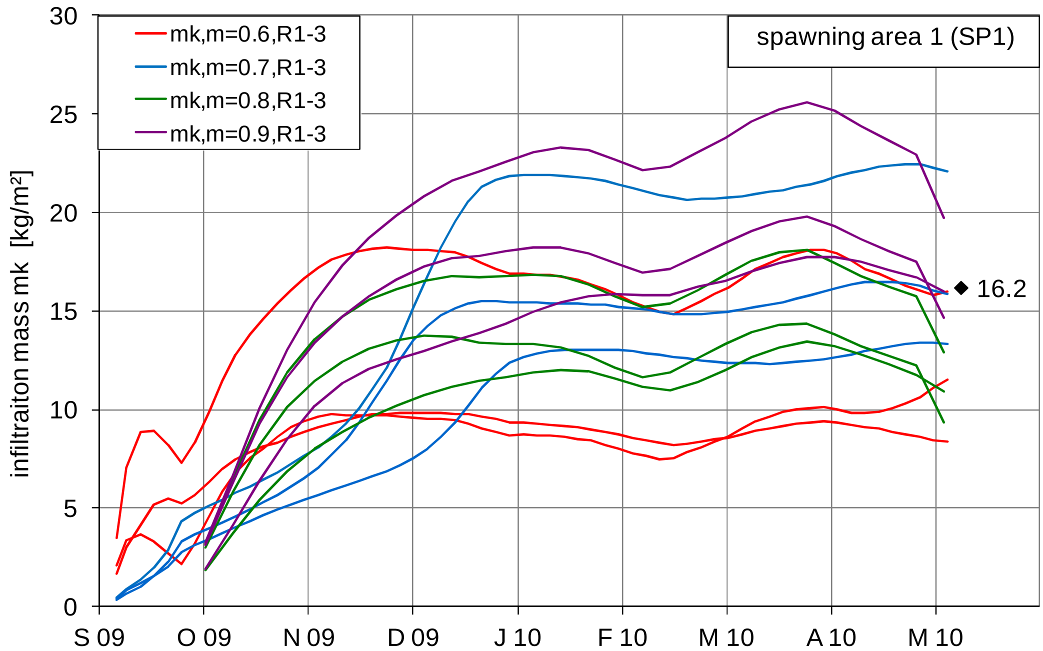


Figure D.2.17: Simulation of sediment infiltration using the numerical model SSIIM2 for different exponents of the hiding/exposure function of Wu et al. (2000)

In Fig.D.2.17 an infiltration during the first 3-4 months is indicated which reach an equilibrium state between deposition and resuspension on approximately January 2010. Further it can be indicated that the equilibrium is achieved for each selected exponent of the hiding/exposure function, although an earlier equilibrium is achieved for the lower exponent values. Neglecting the temporal progress, it seems that an exponent of 0.7 fits best to the measured infiltration masses (m_k=16.2 kg/m²). To adapt the temporal progress of infiltration, additional calibration factors are required to avoid the state of equilibrium in the considered investigation period. Care has to be taken regarding the resuspension of sediments as the simulated particle size distributions after artificial flooding should not be modified. Based on preliminary simulations involving the adjustments of the Shields number, the empirical coefficients of the van Rijn equation (1984) or other factors affecting the critical shear stress were found to be unsuitable, as these calibration factors substantially modified the particle size compositions of the river bed due to higher resuspension rates. The settling velocity is finally chosen for additional calibration as it allows adjusting the equilibrium state between deposition and resuspension without distorting the particle size compositions of the river bed after artificial flooding. A reduction of settling velocities for the fractions transported in suspension (d <2 mm) by a factor of 10 was found to produce reliable results as it is visualized in Fig.D.2.18 (B). Although the settling velocity is a physical attribute and not a typical calibration factor, the reduction by a factor of 10 might be acceptable as variations of settling velocities – especially for fine particles – are likely to occur in natural rivers given to the variations in turbulences, viscosities, particle shapes or in the cohesive behaviour of very fine particles. To allow a comparison of the numerically simulated temporal progress, the simulated values of the semi-empirical approach of Schaelchli (1993) are also illustrated in Fig.D.2.18 (B). Additionally, the simulated spatial patterns of sediment infiltration processes for both approaches at the end of the infiltration period are shown in Fig.D.2.18 (A).

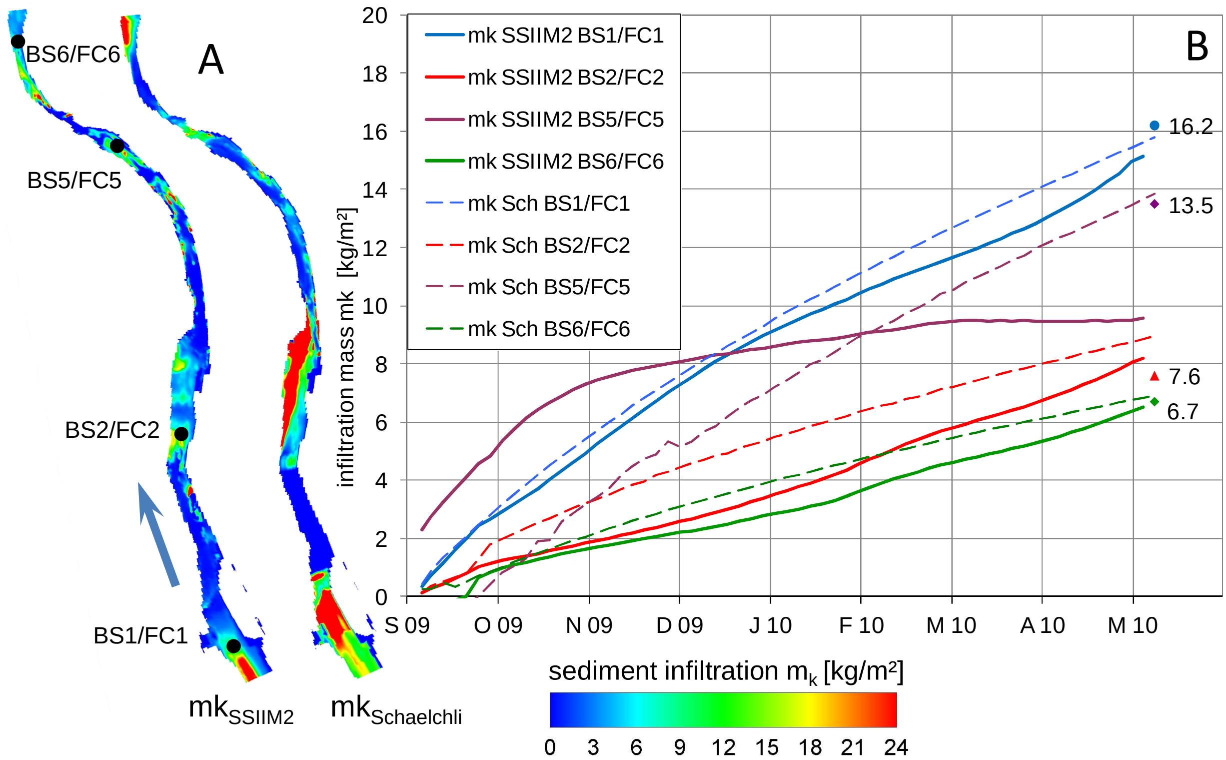


Figure D.2.18: Calibration of simulated sediment infiltration processes in 2009/2010 using the numerical model SSIIM2 contrasted to measured infiltration masses and the simulation results using the semi-empirical approach of Schaelchli (1993)

In the visualization of the spatial distribution of sediment infiltration masses (Fig.D.2.18 A) using SSIIM2 and the semi-empirical approach of Schaelchli (1993) it can be indicated that sediment infiltration occurs roughly in similar areas; mainly at the spawning areas SP1, SP2 and SP3 as well as close to the location BS5/FC5. However, the magnitude of sediment infiltration shows severe differences. This is primarily due to the four main factors – specified by Schaelchli (1993) - affecting infiltration masses (Shields-number, ratio d_{10}/d_m, Re* and the vertical hydraulic gradient). The vertical hydraulic gradient and the ratio of d_{10}/d_m were particularly found to have the highest influences in the River Spoel. The effect of the vertical hydraulic gradient which is explicitly considered in the semi-empirical approach of Schaelchli but not in SSIIM2 is particularly observed at the end of SP1 where relatively high differences between the groundwater level and surface water level were measured. The effect of the approximation of the particle size distribution using the ratio of d_{10}/d_m in the semi-empirical approach of Schaelchli is emphasized in SP2 where high variations of sediment infiltration are simulated in-between cross-sections. The higher infiltration masses on the left border in SP2 are due to a substantially higher d_{10}/d_m (0.24) compared to the right border (0.16). Similarly the discrepancies at the end of SP3 are explained where the values for the ratio of d_{10}/d_m are 0.34 on the left border resulting in high infiltration masses compared to 0.16 on the right border with lower infiltration masses. The four factors influencing sediment infiltration in the semi-empirical approach of Schaelchli are visualized in Appendix 6.3.

A comparison of the total amount of sediment infiltration masses at the measured sediment samples (BS1/FC1-BS6/FC6) of SSIIM2 and the semi-empirical approach of Schaelchli gives similar values, as it is visualized in Fig.D.2.18 (B). The main challenge was to calibrate SSIIM2 according to the temporal progress of the sediment infiltration processes. While for BS1/FC1 and BS6/FC6 the shape of the infiltration curve is reproduced in SSIIM2 with sufficient accuracy, larger deviations are observed for BS2/FC2 and BS5/FC5. For BS2/FC2 high discrepancies occur at the beginning of the infiltration period, particularly in the period when the flow regulation changes from 1.44 m³/s to 0.68 m³/s, afterwards, the relative increase of infiltration masses is reflected properly by SSIIM2. Hence there might be a problem in reflecting the flow transition properly. For BS5/FC5 it can be stated, that the calibration failed completely, as the shape of the infiltration-curve as well as the total amount of infiltration mass in SSIIM2 are totally different to the values obtained by the semi-empirical approach. One reason to explain these enormous discrepancies may be that the location of BS5/FC5 is not in a spawning area (as the others samples) but is located in a highly heterogeneous and turbulent section that includes large boulders which may lead to an inaccurate representation of the hydraulic forces and consequently of the ongoing sediment-transport processes.

<u>Validation of sediment infiltration processes using SSIIM2</u>

Based on the calibration results for the period 2009/2010 a validation of the simulated infiltration masses with SSIIM2 is performed using the abiotic conditions during the infiltration period of 2010/2011. With a total of 313 days this period is substantially longer compared to the infiltration period in 2009/2010. The results of measured and simulated infiltration masses at the sampled freeze-core locations (FC1-FC6) using SSIIM2 and the semi-empirical approach of Schaelchli are shown in Fig.D.2.19. Fig.D.2.19 (A) gives the spatial distribution at the end of the infiltration period while Fig.D.2.19 (B) plots the temporal progress of sediment infiltration.

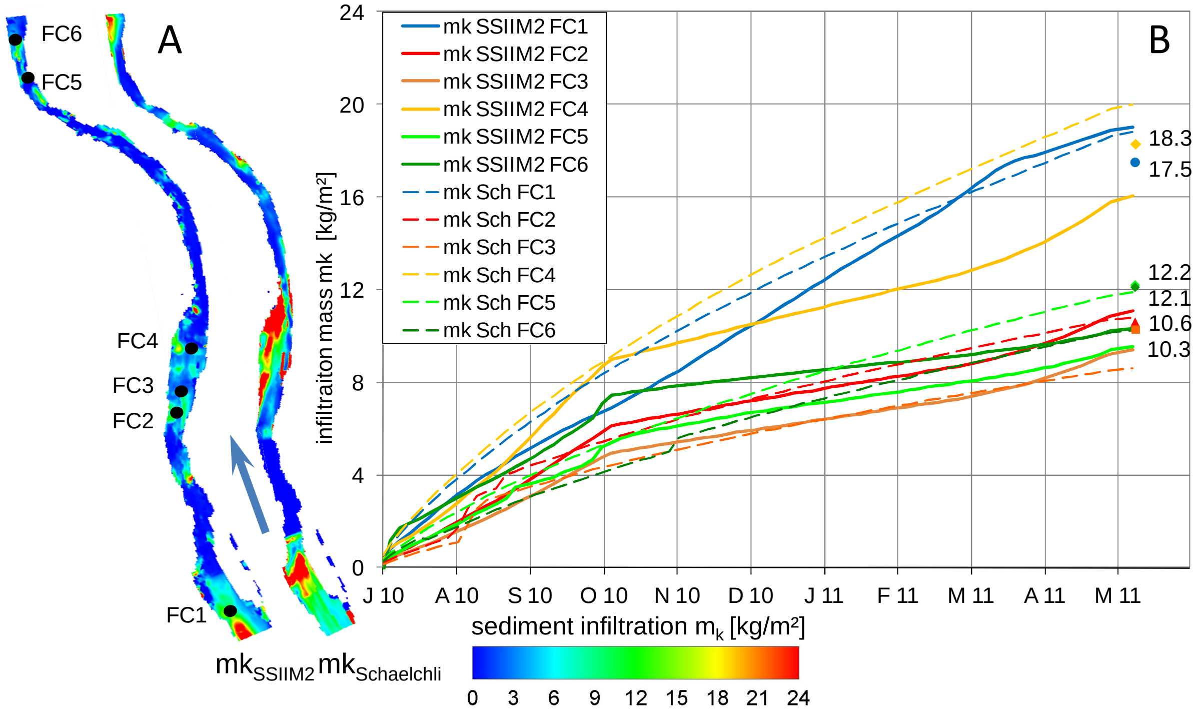


Figure D.2.19: Validation of simulated sediment infiltration processes in 2010/2011 using the numerical model SSIIM2 contrasted to measured infiltration masses and the simulation results using the semi-empirical approach of Schaelchli (1993)

Regarding the spatial distribution a similar picture for the period 2010/2011 can be seen compared to the infiltration period 2009/2010 (Fig.D.2.18 A). Both, the approach of Schaelchli and SSIIM2 identify similar areas of sediment infiltration which also correspond to the areas identified in the period 2009/2010. The visualization of the spatial distribution indicates higher infiltration masses for the semi-empirical approach due to the strong influence of the ratio d_{10}/d_m. In Fig.D.2.19 (B) a good performance of SSIIM2 to both the measured values of sediment infiltration masses and to the semi-empirical infiltration masses is indicated. Larger deviations occur for FC4, which is also shown in the spatial distribution (Fig.D.2.19 A). Given the relatively high vertical hydraulic gradient in that area, the infiltration mass is substantially higher for the semi-empirical approach compared to the numerical model. Given the lack of sediment samples for all characteristic areas of the study site, it is not possible to state which approach is closer to reality. Based on the calibration and validation that uses the sediment samples in the spawning areas (SP1-SP3), it can be stated that SSIIM2 is able to reproduce at least the total mass of sediment infiltration, in regards to the temporal progress a close fitting to the semi-empirical approach could be achieved during the calibration process.

Numerical simulation of variable porosity using SSIIM2

Another important aspect of hypothesis 1 is the inclusion of the interstitial sediment processes which can be described by the temporal and spatial variation of porosity. The porosity is an important input parameter to compute the permeability, which is required to compute the interstitial habitat suitability (Chapter C.1.3). Based on the calibration and validation of SSIIM2 and in regards to the sediment infiltration processes, the predicted variations of porosities are visualized in Fig.D.2.20. Fig.D.2.20 (A) shows an example of the spatial porosity distribution at the beginning and end of the infiltration period 2009/2010, while Fig.D.2.20 (B) describes the temporal variations in porosities.

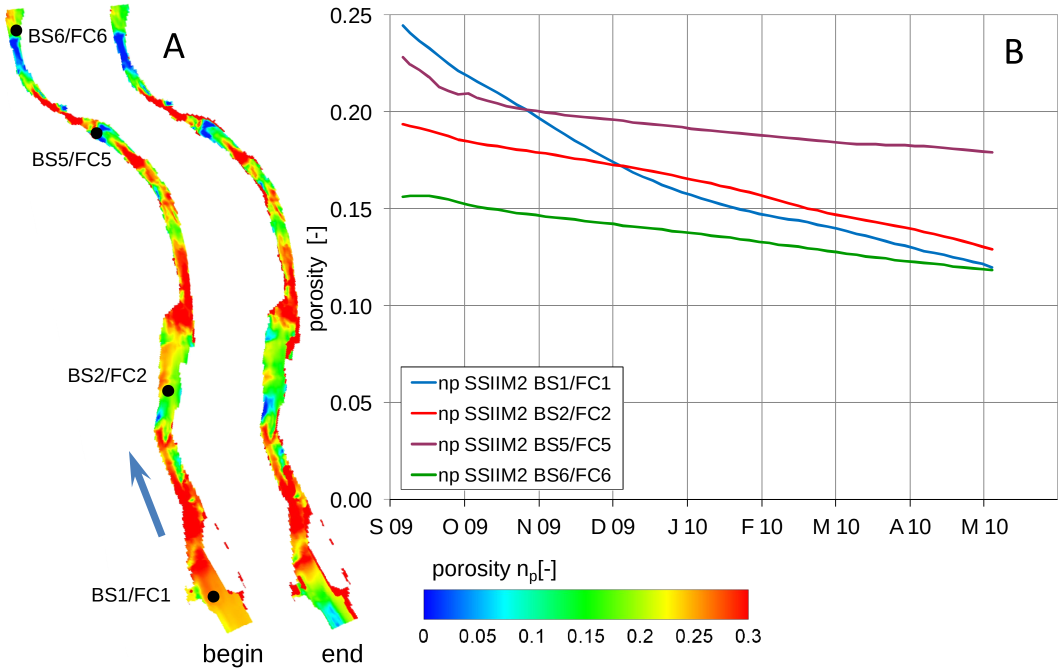


Figure D.2.20: Spatial (A) and temporal variations (B) of simulated porosities of the infiltration period 2009/2010 using the numerical model SSIIM2

The numerically simulated porosities in SSIIM2 are based on Eq.C.1.9 which was specifically developed for sediments of the River Rhine (Germany). A brief comparison of the particle size distribution that were used to develop Eq.C.1.9 (Frings et al., 2011) with typical particle size distributions in the River Spoel yielded that the particle size distributions of the River Spoel are coarser than the particle size distributions in Frings et al. (2011). Thus, the application of Eq.C.1.9 is questionable. Moreover, on the River Spoel no measurements of porosity were feasible leading to no verification possibilities of the simulated porosity values. The spatial distributions of porosities at the beginning and end of the infiltration period show a range of porosities between 0.05 and 0.35, whereby porosities < 0.10 only occur in the pool areas and values >0.30 mainly occur in riffle areas. These porosity ranges are in a typical range for fluvial rivers. According to a brief literature study, performed by Frings et al. (2011), typical porosity ranges are between 0.10 and 0.50 whereby he measured a range of 0.06 to 0.48 in the River Rhine. However, for uniform particle size composition, porosities > 0.40 are generally achieved for an ideal cubical packing assuming the shape of spheres (Frings et al., 2008). Although no verification of simulated porosities is feasible, it is assumed that SSIIM2, based on the comparison to literature values, approximates the temporal and spatial variability of porosity in a range of reliable values.

Furthermore the reduction of porosity due to infiltration of fine sediments is visualized in Fig.D.2.20 (B) showing different porosity reductions of the sampled locations. While for site BS1/FC1 the reduction is > 10 %, it is >5 % for site BS2/FC2 and <5 % for site BS6/FC6. Comparing the temporal progress of sediment infiltration masses to the simulated porosities gives qualitatively a corresponding picture as the highest reductions of porosities are observed for the highest infiltration masses (BS1/FC1) and vice versa. A frequency distribution of porosities at the beginning and end of the infiltration period is presented in Appendix 6.5. The effect of sediment infiltration on porosity is indicated by increasing frequencies for lower porosity values and decreasing frequencies for higher porosity values. The spatial distribution of porosities for the infiltration period 2010/2011, the temporal progress as well as the frequency distribution are shown in Appendix 6.4 and Appendix 6.5.

Discussion

This intermediate discussion aims to evaluate the results obtained from the numerical modelling of sediment infiltration processes in terms of reliability and uncertainty, including the requirements on numerical modelling formulated in hypothesis 1. The ecological relevance as well as the porosity as an input parameter for computing the permeability will be discussed together with the results of the interstitial habitat suitability in the following Chapter D.2.4.

The uncertainties begin during sediment sampling and comprise the locations of sediment samples as well as the accuracy to gather the amounts of fine sediments. To give an idea of the uncertainty during sediment sampling, the fractions of particles >2 mm were varied in a range of ± 0.5 % which is assumed to be likely considering the sampling technique, transport, drying and sieving. This variation range leads to changes in sediment infiltration masses of ± 3.5 kg/m² for BS1/FC1 and ± 1.5 kg/m² for BS6/FC6. The mean percentage deviation for all sediment samples can be stated with approximately ± 20 %. In addition to sediment sampling, model uncertainties have to be considered. Firstly, the assumptions made for missing input parameters have to be taken into account. For the numerical model SSIIM2 this includes the constant incoming sediment-flux, which is not valid for the River Spoel, as the suspended load concentrations are largely driven by precipitation events and snowmelt. Additionally the distribution of the constant flux of incoming sediments over several fractions is highly uncertain due to the lack of data. Further simplifications are made regarding the vertical sorting process as it assumed that sediment infiltration occurs in the surface layer instead of in-between the surface and subsurface layer (Chapter C.1.2.1). For the semi-empirical approach of Schaelchli (1993) the vertical hydraulic gradient is subject to uncertainties as the seepage length is not known and the differences between groundwater level and surface water level is assumed to be temporally constant. Although the flow variations are low during flow regulation, precipitation events may lead to variations of the groundwater level affecting the resulting vertical hydraulic gradient and hence, the sediment infiltration. Another type of uncertainty includes the calibration process itself. As only sediment samples at the beginning and the end of the regarded investigation periods were available no well-funded conclusions regarding the temporal progress of sediment infiltration can be made. In this thesis it is assumed that the semi-empirical approach of Schaelchli gives at least an approximation of the temporal progress. In terms of porosity no verification of the simulated values in SSIIM2 is realizable given the lack of porosity measurements. However, the simulated porosity values are in a typical range of fluvial rivers and the effect of sediment infiltration on porosity values can not only be clearly indicated but also qualitatively reflects the effects of different infiltration masses. Based on the frequency distributions of porosities in both infiltration periods (2009/2010, 2010/2011) a larger shift from high to lower porosities is observed for 2010/2011 which is mainly due to the longer infiltration period and the earlier artificial flooding.

Regarding the reliability of the obtained numerical results it can be stated that SSIIM2 is able to reproduce the sediment infiltration processes with restrictions given to the assumptions that must be made in order for the model to function. Further it is concluded that the obtained numerically simulated infiltration masses are a result of the applied calibration factors (distribution of sediment-inflow, hiding/exposure and settling velocity) that have a very strong influence on the simulations results and can be adjusted to produce a wide range of infiltration masses.

In context of hypothesis 1, it is finally concluded that a 3D-numerical modelling tool can be applied to reproduce the hydromorphological variability with corresponding effects on sediment characteristics (effects of artificial flooding and sediment infiltration) that are required for the reproduction of gravel-spawning fish but significant simplifications of physical processes are required and special care must be taken with regards to the applied formulas, empirical values and calibration factors affecting the numerical results.

D.2.4 Simulation of interstitial habitat suitability (IHS)

Using the numerical output of SSIIM2, the next step of the modelling framework includes the simulation of interstitial habitat suitability (IHS) as an indicator for the abiotic variations of hyporheic conditions including sedimentological characteristics, temperature and respiration (hypothesis 2). In this case study the approach is orientated towards the interstitial requirements of brown trout but generally the approach is applicable for other aquatic species by adapting the formulated interstitial habitat requirements. Firstly, this chapter shows the generation of input data (Chapter D.2.4.1). Secondly, the results of fuzzy-simulation for the IHS-values of the life-stages during the incubation period of brown trout are presented (Chapter D.2.4.2). This chapter is concluded with a discussion about the uncertainty and reliability of the results as well as about the applicability as an indicator for the abiotic hyporheic variability (Chapter D.2.4.3).

D.2.4.1 Input data – Interstitial Habitat Suitability (IHS)

Permeability

The permeability is calculated based on the Kozeny-Carman-Equation (Eq.C.1.12) using a constant viscosity (1.0×10^{-6} m²/s) and the simulated values for porosity and d_{10} obtained from the numerical modelling of sediment infiltration processes with SSIIM2 (Chapter D.2.3.3). Regarding the interstitial habitat suitability the main function of the permeability is to determine if sufficient oxygen is transported through the interstitials and if metabolic waste can be transported downstream. Fig.D.2.21 (A) shows the spatial distribution of permeability at the beginning and end of the reproduction period 2009/2010 while Fig.D.2.21 (B) presents the temporal development of permeability at the locations of the nine artificial redds.

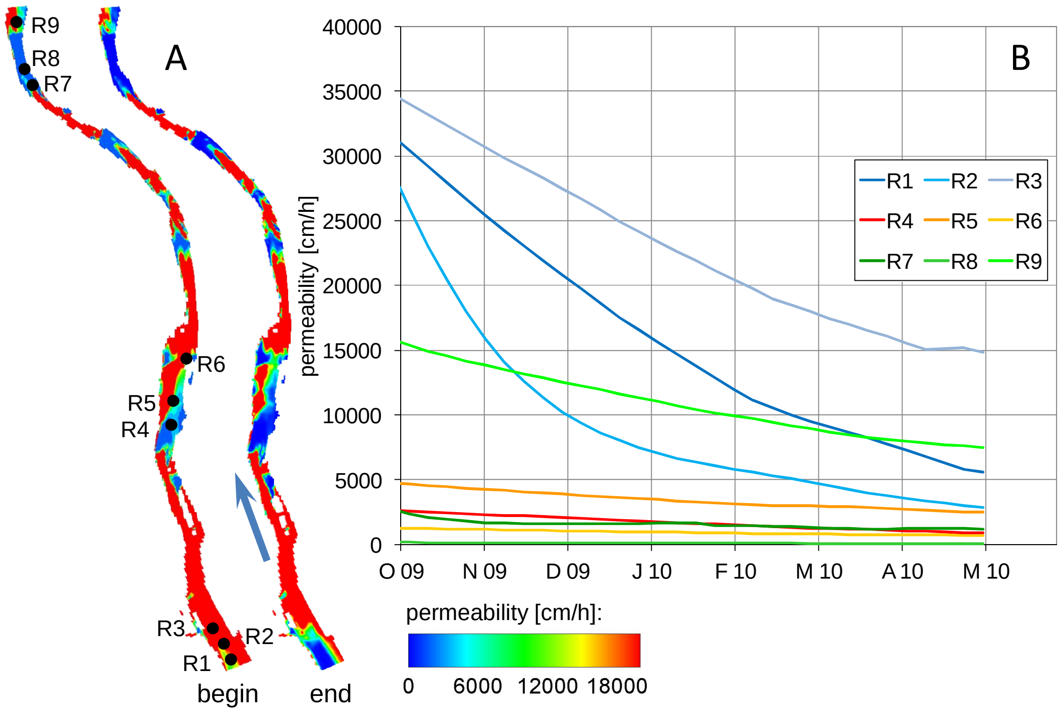


Figure D.2.21: Spatial (A) and temporal variations (B) of simulated permeability during the reproduction period 2009/2010 in the artificial redds R1-R9

According to the visualization of the spatial distribution in Fig.D.2.21 (A) only slight changes are recognizable in the spawning areas SP1-SP3 between the beginning and end of the reproduction period 2009/2010, which is mostly given to the enormous range of occurring permeabilities. Fig.D.2.21 (B) however, indicates strong temporal variations. In SP1 (R1, R2) the permeability is reduced from >25000 cm/h to < 5500 cm/h while for R3 a similar range of reduction is indicated from 35000 cm/h to 15000 cm/h. In SP2 (R4, R6) the magnitude of permeability is substantially lower, ranging from 2000 cm/h to 3500 cm/h at the beginning of the reproduction period to less than 1000 cm/h at the end of the reproduction period. For R5 the permeability declines from 8000 cm/h to 5000 cm/h. In R7 and R8 of SP3 the permeability differs from R9 which is characterized by a higher permeability. While the permeability for R9 is > 15000 cm/h at the beginning, it is only 2500 cm/h for R7 and < 500 cm/h for R8. At the end of the reproduction the permeability of R9 is still > 7500 cm/h while it is 1200 cm/h for R7 and < 100 cm/h for R8.

Although the highest infiltration masses were observed in SP1 - which is also indicated by the strongest decline of permeability - the resulting permeability is still higher compared to SP2 and SP3. This is explained by the different values of d_{10}, which are significantly higher in SP1 (7 mm, R2) as in SP2 (3 mm, R5) and SP3 (5 mm, R9). The other factor affecting the permeability is the porosity which for all spawning areas is in a range of 0.12-0.25 (Fig.D.2.20). The simulated permeability for the reproduction period 2010/2011 and the spatial distributions of d_{10}-values are presented in Appendix 7.1 and Appendix 7.2 respectively.

Interstitial temperature

The function of the interstitial temperature in terms of interstitial habitat suitability is to obtain an idea of the metabolic activity, and generally it can be stated that the higher the temperature is the higher is the activity, which additionally leads to a higher oxygen demand. The interstitial temperature is based on the single data logger located 1200 m downstream of the study site (Chapter D.2.2.1). As this is the only available information about interstitial temperature no spatial variation within the study site is considered in this modelling approach. However, the temporal variation due to seasonal changes is considered as it is visualized in Fig.D.2.22.

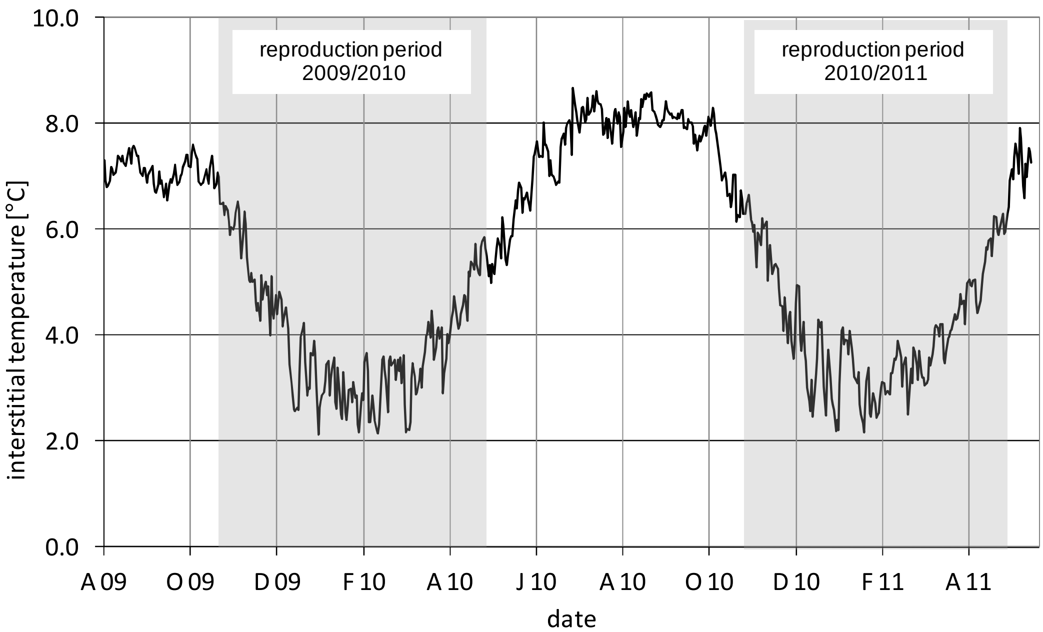


Figure D.2.22: Time-series of measured temperatures 1200 m downstream of the study site

According to the measured water temperatures no recognizable differences between the reproduction period in 2009/2010 and 2010/2011 can be seen (Fig.D.2.22). The highest values during the reproduction periods are at the beginning and end of each period with a temperature around 6.0°C while the lowest temperatures occur from January to March with values around 2.0°C.

Hyporheic Respiration

The hyporheic respiration as a variable describing the summarized oxygen demand due to biogeochemical processes is computed according to Eq.C.1.13 and Eq.C.1.14. The obtained respiration values are based on the measurements of respiration rates conducted by Uehlinger in 2005, the specified layer thickness (Eq.C.1.10) as well as on the numerically simulated porosities and percentages of particle sizes < 8 mm (Chapter C.1.3.1). Fig.D.2.23 (A) shows the spatial distribution of hyporheic respiration at the beginning and end of the reproduction period 2009/2010 while Fig.D.2.23 (B) presents the temporal variations of the respiration values for the nine artificial redds.

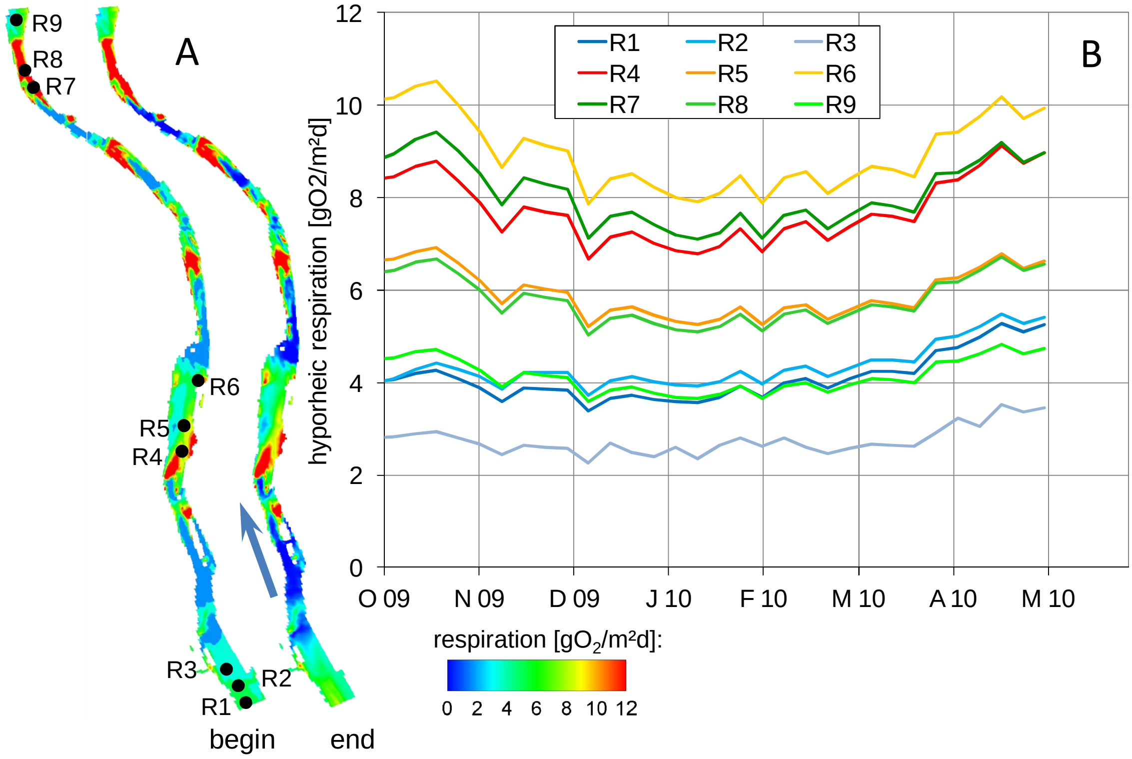


Figure D.2.23: Spatial (A) and temporal variations (B) of simulated hyporheic respiration during the reproduction period 2009/2010 in the artificial redds R1-R9

Given the assumption that the spatial distribution of hyporheic respiration depends on the available surfaces for microbial growth, Fig.D.2.23 (A) shows high respiration values in areas of low porosity and high amounts of particles < 8mm. The time-series of the respiration values further depend on the interstitial temperature as a regulator for metabolic processes leading typically to lower respiration for low temperatures and high respiration values for high temperatures (Fig.D.2.23 B). For SP1 (R1-R3) the respiration values vary between 2.1 gO_2/m^2d and 5.5 gO_2/m^2d. However, until February 2010 the values remain more or less constant and almost no reduction due to lower temperatures in winter can be identified. This implicates the effect of sediment infiltration and the consequential increasing amount of particle sizes < 8 mm which increases the respiration values and thus compensate the reduction due to lower temperatures. After March 2010 a larger increase is identified. This is due to increasing temperatures which surpass the accumulation of particle sizes < 8mm. For R4 and R6 in SP2 the respiration values are higher over the whole reproduction period (6.1 gO_2/m^2d - 10.3 gO_2/m^2d) while R5 in SP2 has similar respiration values as R1 and R2. The higher respiration for R4 and R6 are also explained by the higher amount of fractions of particles sizes < 8mm. In contrast to SP1 a clear reduction of respiration is observed during winter times as the accumulation of particles < 8mm is not as high as for SP1. The highest diversity of respiration is shown for SP3 among the artificial redds R7-R9. The highest respiration is observed for R7 ranging from 9.1 gO_2/m^2d to 7.6 gO_2/m^2d while the lowest respiration is indicated for R9 with a range of 5.3 gO_2/m^2d to 4.0 gO_2/m^2d.

To check the obtained respiration values in terms or reliability they are compared to values in literature and to the measured interstitial values of dissolved oxygen (Chapter D.2.2.1). In literature mean respiration rates of 3.5 gO_2/m^2d were measured for a subalpine river (Uehlinger & Naegeli, 1998) while in a mountainous river in the Pyrenees a mean respiration of 8.0 gO_2/m^2d was found by Capblanq & Lavandier (1975). This fits quite well to the mean respiration value of 4.1 gO_2/m^2d determined for the River Spoel. The comparison to the measured interstitial DO values (presented in Appendix 7.4) is only of a qualitative character, yet two aspects are indicated: the decrease of respiration values during the winter is in coincidence with the increase of measured DO-concentration and also the spatial distribution, when comparing the single lines, a similar ranking can be seen (e.g. DO2 and DO3 are characterised by the lowest DO-concentrations and the highest respiration values). It can therefore be stated that the respiration values are at least in a reliable range and provides a well approximation of the oxygen demand in the study site. The time-series of respiration values in 2010/2011 in all artificial redds are shown in Appendix 7.3.

D.2.4.2 Results – Interstitial Habitat Suitability (IHS)

Based on the fuzzification of the input parameters and the developed fuzzy-rules (Chapter C.1.3.1, Appendix 2.1), the permeability, interstitial temperature and the hyporheic respiration are linked to an interstitial habitat suitability which distinguishes between the different life-stages during the incubation period (eyed-eggs, hatching, and larvae) according to their different habitat requirements. The obtained results are analysed regarding their spatial distribution and regarding their temporal variability during incubation. In addition, areas of equal IHS-values, normalized by the wetted area, are calculated to provide information about the supply of interstitial habitats over the entire study site.

<u>Spatial distribution of IHS-values</u>

Fig.D.2.24 shows the spatial distribution of input parameters at the most critical stage, which is at the end of the hatching period (as highest requirements on the interstitial quality are demanded) as well as the most critical IHS-values in each life-stage during the incubation period of 2009/2010. The spatial distributions of the input parameters and resulting IHS-values are only a temporal snapshot but work well to demonstrate the functionality of the fuzzy-model. In general the interpretation is done in two steps: firstly, it must be controlled in which membership function the input variables are located (at a current time-step) and in a following step the correspondingly activated rules have to be identified in the set of fuzzy-rules additionally considering how well each activated rule reflects the abiotic input conditions.

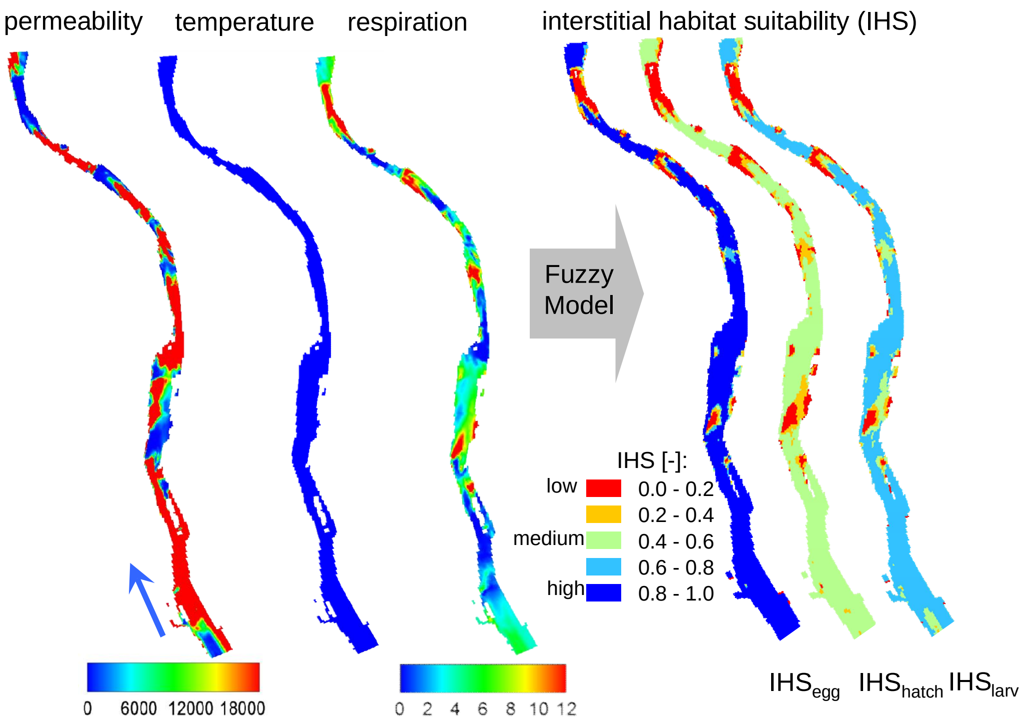


Figure D.2.24 Spatial distribution of in- and output parameter to simulate the interstitial habitat suitability for the life-stages eyed-egg, hatching and larvae (IHS_{egg}, $IHS_{hatching}$, IHS_{larv}) during the incubation period 2009/2010

Fig.D.2.24 generally indicates a 'very high' IHS-value for the eyed-eggs, a 'medium IHS-value for hatching and a 'high' IHS-value for the larval stage. In all life-stages areas with lower IHS-values are identified which represent zones with strong sediment infiltration and a consequently 'very low' or 'low' permeability. The overall differences between the life-stages occur due to the different habitat requirements, which are highest for the hatching stage and lowest for the eyed-egg stage. The overall equal reduction of IHS-values (e.g. for the hatching stage) indicates the strong influence of interstitial temperature, which is spatially constant at a given time-step. Consequently, if the temperature reaches a limiting value, it equally affects the entire study site. In Fig.D.2.24, a temperature of 2.1°C is shown at the most critical time-step during the hatching stage which is part of the 'low' membership function leading predominantly to 'medium' IHS-values. Thus, the values of IHS_{hatch} are lower compared to IHS_{egg} and IHS_{larv}, where higher temperatures (4.5°C, 2.9°C) are present that do not limit the IHS-value in the same magnitude compared to the hatching stage. The respiration values are widely allocated to the 'low' membership function indicating less influence on IHS-values. However, in areas with 'medium' and 'low' permeability, 'medium' respiration occurs that limits the IHS-values. The spatial distributions of the simulated IHS-values in the incubation period 2010/2011 are shown in Appendix 7.6.

Temporal variation of IHS-values

The previously performed spatial interpretation represents only a single time-step of the total reproduction period. The dynamically changing IHS-values according to the hyporheic variability expressed by the input parameters are of major concern to evaluate the quality of the interstitial habitats in terms of the reproduction of brown trout. Fig.D.2.25 (B) therefore shows examples of time-series of simulated IHS-values for each life-stage in the artificial redds R2, R5 and R9 in the incubation period of 2009/2010. For orientation Fig.D.2.25 (A) shows the spatial distribution of IHS-values at the end of the hatching stage.

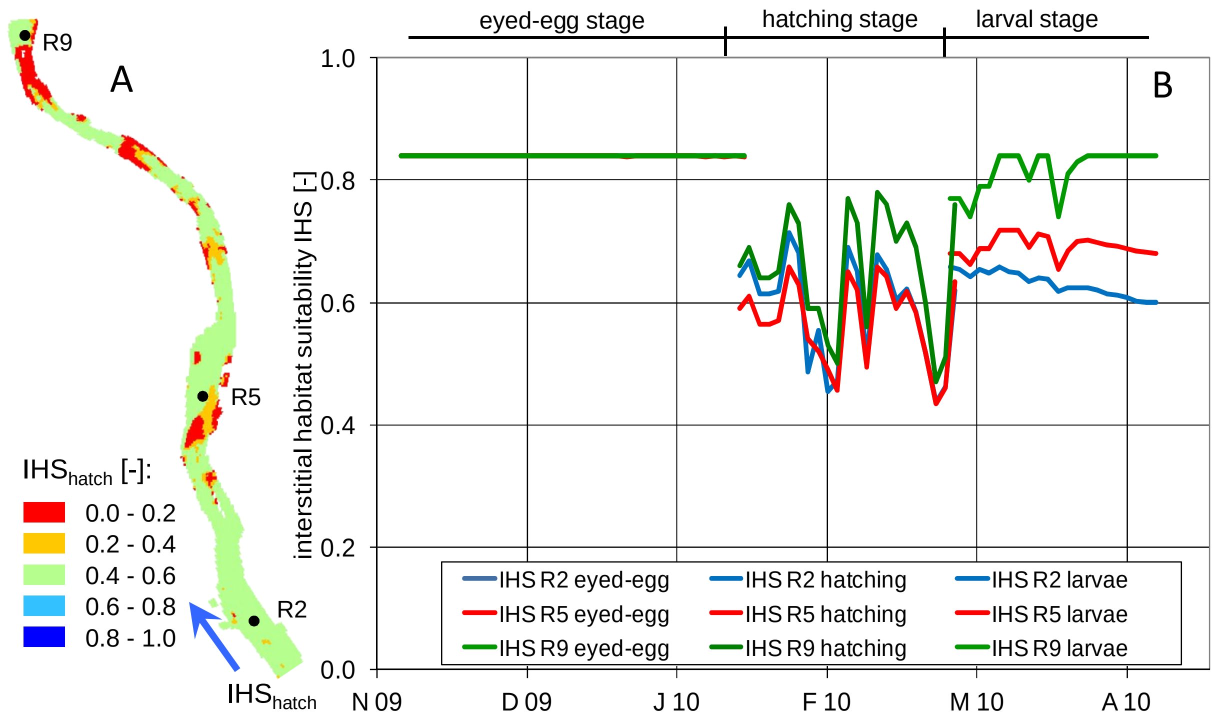


Figure D.2.25: Temporal variations of simulated IHS-values (IHS_{egg}, IHS_{hatch}, IHS_{larv}) during the incubation period 2009/2010 at the artificial redds R2, R5 and R9

For interpretation purposes it is noteworthy, that the highest theoretical IHS-value is 0.84 while the lowest is 0.16 given to the specification of the fuzzy-sets for IHS-values (see also Chapter C.1.4). For the eyed-egg stage in R2, R5 and R9 (Fig.D.2.25 B), only ‘very high’ IHS_{egg} are simulated. This is reasonable as the permeability for all redds is > 3000 cm/h, which is in the ‘medium’ membership function providing sufficient interstitial quality for eyed-eggs. Further, the temperature does not fall below 4 °C, which lies also in the ‘medium’ range providing optimal conditions, and the hyporheic respiration is for all redds ‘low’, which does not limit the interstitial quality at all. Similarly, the interpretation is done for the hatching stage. All IHS-values are significantly lower compared to the eyed-egg stage given to the higher requirements during the hatching stage. Strong variations for all redds can be indicated during the hatching stage. These fluctuations are in a range of ± 0.3 resulting from the temperature variations close to the limiting values of 2°C – 3°C. For values < 3°C lower IHS-values are simulated compared to temperatures > 3°C. The shape of these fluctuations as shown in Fig.D.2.25 (B) is similar for all redds as the temperature affects them all in an equal manner given to the constant spatial distribution of the temperature. The differences in magnitude of IHS between the redds occur due to different permeabilities which all belong to the ‘medium’ and ‘high’ memberships functions but the degree of membership varies between the redds (e.g. the permeability in R9 belongs with higher rates to the ‘high’ membership function and less rates to the ‘medium’ one compared to R2 and R5). The respiration values are in the ‘low’ and partly in the ‘medium’ range and have no major limiting consequences within the spawning areas SP1-SP3. Lastly, the fuzzy-simulations for the larval stage indicate the highest interstitial quality for R9, followed by R5 and R2. Altogether the IHS-values are slightly higher compared to the hatching stage, although the permeability is in all redds lower compared to the hatching stage given to a higher infiltration masses (Chapter D.2.3.3) and a higher oxygen demand occurs during the larval stage (Chapter A.2.2.5). This is explained by the higher tolerance of larvae to abiotic conditions and the limited mobility of larvae to avoid extreme abiotic conditions. Moreover, oxygen is obtained through the gills of the larvae which is much more effective comparing to the diffusion through the egg shell. The difference between R9 and R5 is caused by the 'high' and partly 'medium' permeability for R2, while R9 is still totally in a 'high' range for permeability. Interestingly the IHS_{larv} for R2 is continuously decreasing. This represents the strong decline of permeability in this redd. For the fuzzy-model this means a continuously increasing portion to the 'medium' membership function while the portion belonging to the membership function 'high' is accordingly decreasing leading consequently to a continuous reduction of the IHS-value.

Based on an analysis of the temporal variations of IHS-values considering all redds (Appendix 7.5) it is indicated that highest IHS-values are obtained for SP1 (R1-R3), although this area has the highest sediment infiltration masses. But the resulting permeability remains within a suitable range and is able to sufficiently transport oxygenated water for the development of eggs. For SP2 (R4-R6) the simulated IHS-values are mainly in the 'medium' range while for SP3 (R7-R9) a sizeable difference between R7, R8 and R9 can be seen. For R7 the simulated IHS-values during hatching are 'low' while for R8 they are close to zero indicating very poor interstitial conditions. The strong reductions in R7 and R8 are mainly due to the low permeability in this area. For R7 the permeability is < 1200 cm/h and in the 'low' membership function, while for R8 the permeability is < 100 cm/h and in the 'very low' membership function.

The simulation of dynamically varying IHS-values allows for a precise interpretation of the abiotic conditions of the interstitial habitat conditions at different time-steps and the fuzzy-model is able to represent limiting conditions appropriately. This is best illustrated with the occurring variability of IHS-values during the hatching and larval stage, indicating that the approach is able to reflect shortly upcoming limiting factors like critical temperatures but also long-term events like the effects of sediment infiltration which leads to continuously decreasing IHS-values.

Supply of interstitial habitats

To evaluate the supply of interstitial habitats, the areas of equal IHS-values are evaluated for each life-stage during the incubation period. To compare both reproduction periods the obtained areas are normalized by the wetted area in each time-step resulting in time-series of areal percentages of IHS-classes as it is illustrated in Fig.D.2.26.

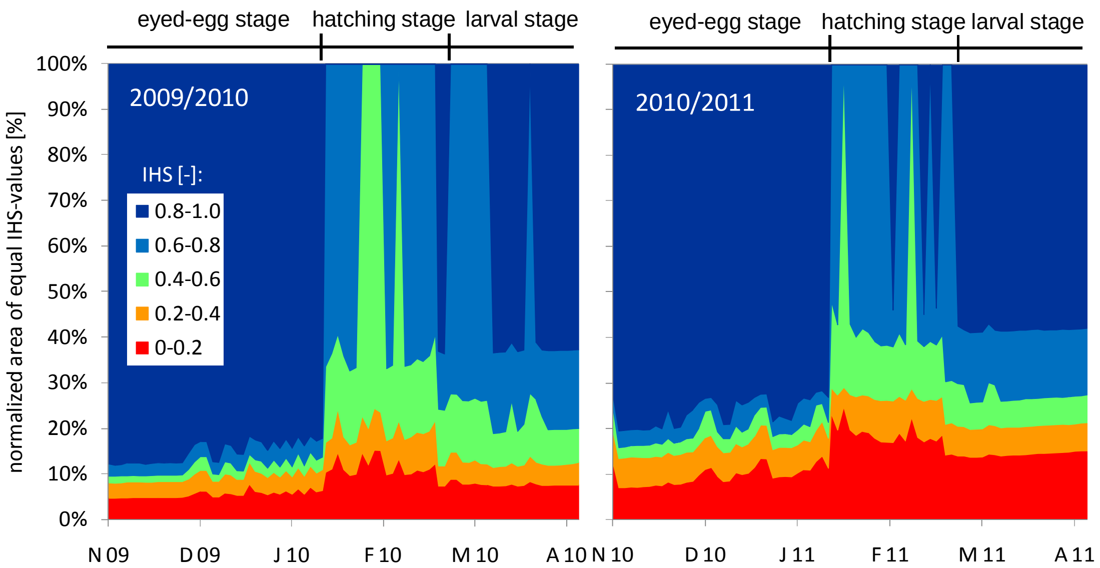


Figure D.2.26: Time-series of normalized areas of equal IHS (IHS_{egg}, $IHS_{hatching}$, IHS_{larv}) in both incubation periods (2009/2010, 2010/2011)

Similarly to the interpretation of the spatial distribution (Fig.D.2.24), Fig.D.2.26 indicates that for both reproduction periods there are wide areas of ‘high’ and ‘very high’ IHS-values due to the wide areas of the study site that are characterised by coarse particle size distributions and low amounts of fine sediments. Additionally Fig.D.2.26 allows the identification of the different habitat requirements during incubational life-stages. According to the normalized areas of equal IHS-values, the same ranking in terms of habitat requirements is identified whereby the most tolerable stage is the eyed-egg stage, which is followed by the larval stage and lastly, the most critical hatching stage with the highest habitat demands. Another aspect indicated by the figure is the continuously increasing area of ‘low’ IHS-values which describe a progressing increase of limiting interstitial habitat conditions. Compared to the total wetted areas this increase is relatively low. The peaks in the hatching stage of IHS-classes 0.4 to 0.8 reflect the effects of the varying temperature close to the critical range of 2°C – 3°C, which reduces the IHS-values for the whole study site. Comparing both reproduction periods against each other, give a generally similar pattern of the normalized areas in 2009/2010 and 2010/2011. However, differences occur for not suitable areas which are considerably higher in 2010/2011 which is explained by the substantially longer time period between artificial flooding and the incubation period (75 days in 2009/2010 and 140 days in 2010/2011). This allows a longer infiltration of fine sediments and consequently resulting in higher infiltration masses during the incubation period which is also confirmed by the monitoring (Chapter D.2.2.1) and simulation results (Chapter D.2.3.3).

D.2.4.3 Summary and discussion – Interstitial Habitat Suitability (IHS)

To evaluate the results obtained from the fuzzy-model to simulate the interstitial habitat suitability as an indicator for the hyporheic variability (hypothesis 2), the uncertainty of the habitat describing variables and the fuzzy-approach are discussed. Additionally the functionality of the fuzzy-model as an indicator is verified based on the general indication criteria formulated in Chapter A.2.2.4.

Reliability and uncertainty of input variables

The uncertainty of the input variable permeability – as an indicator for the transport of oxygenated water and metabolic waste products – is predominantly determined by the quality of the numerical results. The extreme variability of permeability in natural rivers encompasses several orders of magnitude within small areas. Only slight changes of the numerically simulated porosities lead to immense variations in permeability (as it was found in the sensitivity analysis for the flume in Chapter D.1.2.2). Therefore an evaluation of the permeability on the scale of single computational elements is hardly feasible. However, general trends of characteristic areas of the River Spoel can be identified with reasonable values of permeability. The most restricting issue is the missing measurements of permeability. Although the numerical results were calibrated and validated for bed level changes and particle size distributions, a verification of the obtained permeability based on monitoring results are indispensable for a trustworthy representation of the spatially and temporally varying permeability.

The interstitial temperature – reflecting the metabolic activity and upper and lower lethal and sub lethal limits – is assumed to be spatially constant which might not be true given to up- and downwelling processes with corresponding mixing processes of surface water and groundwater affecting the resulting interstitial temperature. This might play a role if the temperature in surface water is close to the critical limit of 2°C – 3°C, as for groundwater a constant temperature of 4°C can be assumed which can maintain the interstitial temperature in a suitable range. However, groundwater is also characterized by low contents of dissolved oxygen which certainly have a negative impact on the quality of the interstitial habitat. This aspect is only relevant in the two upwelling zones that were identified in the River Spoel (Chapter D.2.2.2).

The hyporheic respiration – reflecting the influence of biogeochemical processes on the oxygen availability during incubation – is based on the mean measured values, the spatial distribution is calculated based on porosity and the amounts of particles < 8mm and the temporal variation is based on the Arrhenius equation (Eq.C.1.14). This procedure is more a rough estimator of the on-going biogeochemical processes than an accurate modelling approach. A qualitative comparison of the hyporheic respiration to the measured dissolved oxygen concentration gives a good approximation of the temporal and spatial variations which might indicate that the obtained respiration values in the River Spoel are at least qualitatively reliable. Compared to the other both habitat variables, the respiration in the River Spoel have no dominating character as the amounts of organic material are generally low and the respiration values are almost not in limiting ranges.

Fuzzy-approach to simulate IHS-values

Given the aforementioned assumptions and uncertainties the fuzzy-approach seems to be an appropriate tool to estimate the quality of interstitial habitats. The degree of fuzziness is regulated by the number and the degree of overlapping membership functions that are specified for each input variable. For the permeability and temperature five functions are chosen, while for the respiration only three functions are specified. While the five functions for temperature are chosen due to the relatively good expert-knowledge about the effects of temperature on life-stages during the incubation period, the five functions for the permeability are required to cover the immense range of occurring permeabilities in the River Spoel. The three functions for respiration are chosen given to the uncertainty and assumptions included in the procedure to determine the respiration values, thus this is the most imprecise parameter. The fuzzy-rules – determining the interactions of the input variable on IHS – are defined based on literature values and from close collaboration with biologist Johannes Ortlepp, who worked over ten years in the River Spoel on investigating the brown trout population, to assure the application of highest available expert-knowledge.

Analysis of the outcomes of the fuzzy-modelling has shown that the fluctuations are predominantly invoked by the variations of the interstitial temperature close to the critical range of tolerated temperatures. This is evidently visible for the hatching stage, as limiting temperatures meet the highest requirements on interstitial habitats leading to fluctuation between 'high' and 'medium' IHS-values. Regarding the effect of permeability it is observed that the permeability mainly determines the magnitude of the IHS-values, however a continuously decreasing IHS-value is also recognized, particularly during the larval stage. The influence of hyporheic respiration is almost not limiting the IHS-values within the spawning areas.

The obtained simulated IHS-values for the life-stages eyed-eggs, hatching and larvae consider the different habitat requirements of the life-stages which are highest for the hatching stage and lowest for the eyed-eggs. Naturally the habitat requirements do not immediately change from one life-stage to another but will change continuously. This aspect is not considered in the fuzzy-sets and fuzzy-rules leading to abrupt variations of IHS-values in the transition of two life-stages.

Functionality of IHS-values as an indicator for hyporheic variability

The general requirements of an indicator are presented in Chapter A.2.2.4 and are specified for the hyporheic quality in Chapter B.2. To evaluate the functionality of IHS-values as an indicator for abiotic hyporheic variability, the incubation habitat must be described adequately and the general indication criteria must be met (Chapter B.2.4). According to the four key factors describing the incubation habitat (hydromorphological variability, dissolved oxygen, hyporheic exchange, and interstitial temperature, Tab.B.2.3) the fuzzy-approach approximates the hydromorphological variability using the permeability of the river bed and the interstitial temperature as a direct input variable of the fuzzy-model. The dissolved oxygen is described by the respiration that describes the oxygen demand of biogeochemical processes and by the permeability that describes the transport capability of oxygenated water through the interstitial of the river bed. A restriction has to be made regarding the hyporheic exchange which is neglected in the whole modelling framework. Information about hyporheic exchange processes like up- and downwelling, interstitial flow paths, residual times of water etc can have enormous effects on biogeochemical processes and consequently on the abiotic conditions of the interstitial habitat (Chapter A.2.3). To consider these aspects further, coupled surface-groundwater simulation tools would be beneficial for a proper estimation of hyporheic exchange processes.

In terms of the general indication criteria (Chapter A.2.2.4) it can be stated that the conceptual relevance and interpretability is fully given as the IHS-values react highly sensitive to variations of input variables and the obtained IHS-values are comprehensible in respect to the fuzzy-sets and fuzzy-rules. Minor restrictions are made for practical aspects. The practical aspects to obtain IHS-values include a representative monitoring concept of all involved parameters in a sufficient spatial and temporal resolution as well as the numerical and fuzzy modelling. Together the efforts in monitoring and modelling are quite high but indispensable to get reliable IHS-values. Although the response variability can be assigned to the effects of varying input-conditions it is not known what a reduction of IHS-values explicitly means in a biological or ecological meaning. For instance, what does it mean in an ecological point of view if the IHS-values is 0.3 or 0.4? To overcome this lack of knowledge the fuzzy-model has to be applied on reference sites so that data of a pristine river reach can be compared to the data in a modified river reach to allow for well-founded ecological assessments (Chapter A.2.5).

In conclusion, the obtained results within the context of hypothesis 2 are that the multivariate fuzzy-model used to simulate IHS-values provides highly valuable information about the hyporheic variability. A restriction has to be made regarding the proper representation of hyporheic exchange processes and the verification of the obtained simulation results. Nevertheless, the spatially and temporally changing interstitial habitat conditions allow firstly a dynamic assessment of the hyporheic variability which can have a detrimental impact on the quality of reproductive habitats.

D.2.5 Simulation of physical habitats during reproduction

With the simulation of the IHS-values all required input parameters for physical habitat modelling with CASiMiR are available. The following section gives the resulting temporal and spatial variability of HSI-values separated for each life-stage during reproduction - spawning, incubation, and emergence - while the incubation period is further subdivided into the eyed-egg-stage, hatching stage and larval stage (hypothesis 3). To define the time periods for each life-stage the empirical equations developed by Crisp (1996) are applied (Appendix 8.1). Each chapter provides detailed information about the model input, the obtained results and a concluding discussion. The physical habitat model is applied for both reproduction periods (2009/2010, 2010/2011) using the same fuzzy-sets and fuzzy-rules (Appendix 2, Chapter C.1.4).

D.2.5.1 Spawning habitats

The first life-stage considered in the reproduction period is the spawning stage. According to the equations of Crisp (1996) the spawning period in the River Spoel can be identified from mid October to mid November (depending on the water temperature, Appendix 8.1). To simulate the spawning habitat suitability (HSI_{spawn}) the two-stage fuzzy-approach described in Chapter C.1.4 is applied using the fuzzy-sets and fuzzy-rules specified in the Appendices 2.4-2.6. In a first step the spawning sediment index (SSI) is calculated using the classified particle distribution according to Fig.C.1.6 which is then further used as an input variable for the second step where it is combined with the hydrodynamic variables of flow velocity and water depth.

Input-data – spawning habitats

In the study site six parameters in total are used to describe the spawning habitat. The substrate characteristics are described using the classified particle size distribution including sand (< 2mm), gravel (2-31 mm), pebbles (31-64 mm) and cobbles (>64 mm) while the hydraulic characteristics are described using water depths and flow velocities. All input data are a direct output of the numerical model SSIIM2. Fig.D.2.27 shows the spatial distribution of each habitat variable at the end of the spawning period 2009.

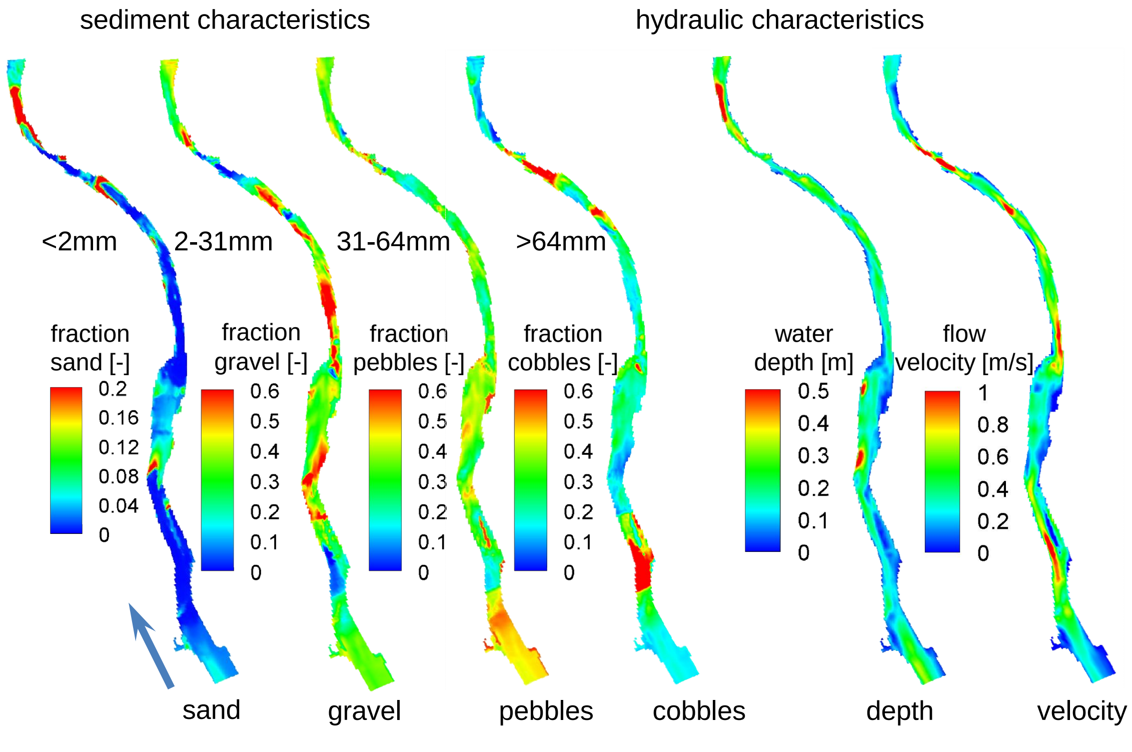


Figure D.2.27: Spatial distribution of sedimentary and hydraulic input parameters to simulate the habitat suitability index (HSI_{spawn}) in the spawning period 2009

The spatial distribution visualized in Fig.D.2.27 indicates for the sand fraction wide areas with percentages less than 5% and that only in the pool area of SP3 values higher than 20% are present. This is primarily due to the pool, which acts as a sediment trap where fine sediments can accumulate. These values (except of the pool area) are part of the 'low' membership function of the fuzzy-sets for SSI and are not critical for spawning as long as the other fractions are in a suitable range. The spatial distribution of the gravel fraction shows a wide range of different percentages from less than 10% to more than 60%. However, in the spawning areas SP1-SP3 the amounts of gravel are not as varied, ranging from 30% to 40% which are mainly allocated to the most suitable membership function ‘medium’ and only partly to the ‘high’ membership function which is marked by ‘low’ and ‘medium’ suitability. In contrast to the gravel fraction, the pebble fraction is marked by lower variations for the whole study site while the variation in the spawning areas is similar, ranging from 35% to 45%. These values are within the membership function ‘medium’ providing suitable spawning habitat conditions. The spatial distribution of cobbles allows a clear identification of the riffle areas where percentages of more than 60% are simulated, while in-between considerably lower percentages ranging from 15% to 30% are identified. In all spawning areas the values are below 40% which is the threshold according to the habitat requirements formulated in the fuzzy-sets and fuzzy-rules.

Regarding the hydraulic parameters it can be stated that the study site is characterised by very shallow water depths ranging in the spawning areas from 0.15 m to 0.30 m which are not critical for spawning. The flow velocities are characterized in the spawning areas in a range of 0.25 m/s to 0.35 m/s which are part of the ‘low’ and ‘medium’ membership function whereas ‘medium’ flow velocities are more suitably compared to ‘low’ flow velocities. A similar analysis can be performed for the spatial distributions of input parameter in the spawning period 2010 which are shown in Appendix 8.4.

The temporal variation of the input parameter during the spawning period is of minor relevance as the variations are low. In Appendix 8.2 and 8.3 the time-series of the input parameter are visualized for the artificial redds R2, R5 and R9 for both spawning periods (2009, 2010), confirming relatively steady values over both spawning periods. Considering the previous analysis the habitat variables within the spawning areas are between moderate and preferred ranges for spawning brown trout. However, the combined effect of all habitat variables is subject to the two-stage fuzzy approach presented in the following chapter.

Results – spawning habitats

The obtained simulated values for the spawning sediment index and habitat suitability index for spawning are based on the fuzzy-sets and fuzzy-rules presented in the Appendices 2.4-2.6. These sets and rules are applied for both spawning periods (2009, 2010). The simulated values for the first fuzzy-step (SSI) as well as for the second step (HSI_{spawn}) are analysed according to their spatial distribution and their habitat supply - expressed by the areas of equal SSI and HSI_{spawn} - to obtain an integrative result of the entire study site in the River Spoel.

Spatial distribution of HSI_{spawn}

Fig.D.2.28 illustrates the obtained simulation results for both fuzzy-steps (SSI, HSI_{spawn}) in both spawning periods (2009, 2010). To verify the spatial distribution of spawning habitat qualities, they are compared to the mapped spawning redds in 2009 and 2010 respectively. For a better visualization the simulated HSI_{spawn} are plotted twice. The first visualization is without the mapped spawning redds and the second visualization is with the mapped spawning redds that are marked by black squares. The attached number gives the number of counted redds in this area.

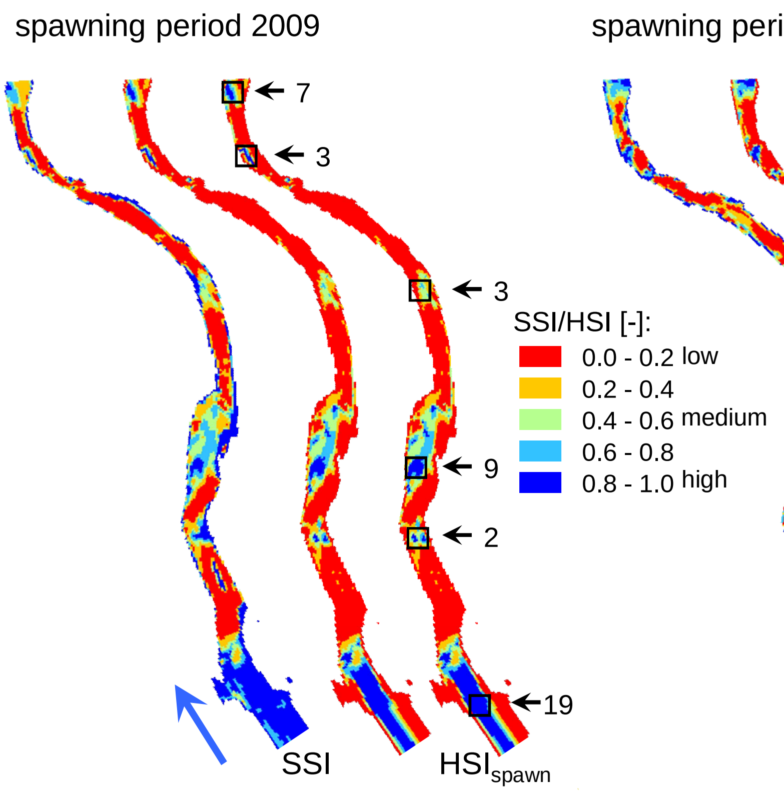


Figure D.2.28: Spatial distribution of the spawning sediment index (SSI) and spawning habitat suitability index (HSI_{spawn}) for the spawning periods in 2009 and 2010. Additionally the mapping results of spawning redds in each spawning period are visualized

Spawning Sediment Index (SSI)

The sediment spawning index SSI aims to evaluate in a first step the sediment characteristics for the selection of suitable spawning grounds for brown trout based on the aforementioned classification of the particle size composition. In 2009 a 'very high' SSI-value is simulated for SP1 which is roughly characterised by a 'low' amount of sand (< 5 %), a 'medium' amount of gravels (35 %) and pebbles (45 %) and a 'low' amount of cobbles (15°%). Compared to the preferred ranges in Tab.C.1.6 this composition reflects more or less an ideal condition for spawning purposes of brown trout. The riffle area downstream of SP1 is not suitable due to high amounts of cobbles (>60 %) which a spawning fish cannot move during redd digging. At SP2 the SSI-values are marked by a higher diversity providing sizeable areas with SSI-values in the range of 'medium' to 'very high'. Between SP2 and SP3 most areas are not suitable except for one patch located in the left bend of the study site. Upstream of SP3 the SSI is also not suitable given to the riffle characteristic with high amount of cobbles (> 60%) and blocky material. At SP3, only the most downstream area provides values in the range of 'low' and 'high' SSI-classes. The area upstream is not suitable given to the large pool where 'high' amounts of sand are deposited.

The SSI-values in the spawning period 2010 generally show a similar spatial distribution as the spawning period 2009. Differences are identified at SP2 with more areas in the 'very high' range of SSI-values and in the area between SP2 and SP3, which is characterised by patches of different sizes having mostly SSI-values in the 'low' and 'medium' range, but also single patches with 'high' and 'very high' SSI-values. Moreover, SP3 shows sizeable areas with 'high' and 'very high' SSI-values except of the pool area where 'high' amounts of sand are located.

Habitat Suitability Index for spawning (HSI_{spawn})

The simulated values of SSI are combined in a second fuzzy-step with the hydrodynamic variables flow velocity and water depth. For both spawning periods a strong dominance of the SSI-values are indicated in Fig.D.2.28, as the spatial distribution of suitable and not suitable HSI-values are very similar to the simulated SSI-values. However, the extensions of the areas with SSI > 0 are considerably reduced by the hydrodynamic variables. This aspect is recognizable predominantly for SP1 and SP2 as well as to a minor extent for SP3. The reductions encompasses mainly the areas close to the river banks that are characterised by ‘low’ and ‘very low’ flow velocities (< 0.1 m/s) which limit the values of HSI_{spawn} as the fine material which is exposed during digging cannot be transported downstream. Compared to the flow velocity, the water depth is of minor relevance as only sufficient water depth is required to maintain manoeuvrability for the spawning process. Comparing the simulation result of the spawning period 2009 and 2010 confirms the dominant behaviour of the sediment characteristics in simulating spawning habitat qualities. The patchy distribution of SSI-values between SP2 and SP3 is also reflected in the distribution of HSI_{spawn}, although the extension of the patches is sizable reduced by the hydrodynamic variables. For this area this is mainly due to ‘high’ and ‘very high’ flow velocities (> 0.8 m/s) where it is difficult for spawning brown trout to hold position over the spawning redd.

Based on the analysis of the spatial distribution of spawning habitat quality it can be stated that the description of sediment characteristics using SSI-values clearly dominates the quality of habitats in the River Spoel. The flow velocity is also an important factor giving upper and lower limits for spawning habitat quality to assure the transport of digging material downstream and to assure that the spawning fish is able to hold position over the redd without investing too much effort. The water depth is of minor relevance.

Comparison to the mapping results of natural spawning redds

Comparing the simulated habitat spawning qualities of CASiMiR to the mapping results of the natural spawning redds a good approximation is indicated for the spawning season 2009 (Fig.D.2.28). Almost all natural redds (43) are located in areas with a ‘high’ or ‘very high’ habitat suitability index. In addition, the number of counted redds is slightly correlated to the size of the suitable spawning areas. This is explicitly visible for SP1 where 19 redds were counted and correspondingly a wide area of ‘very high ‘suitability is simulated or for the smaller patch between SP1 and SP2 where only 2 redds were counted. For the spawning season 2010, the mapping results differ from those of spawning season 2009. The locations of the mapped redds (48) are much more distributed over the entire study site and also within each spawning area. A comparison with the simulated spawning habitat qualities assures the functionality of CASiMiR to simulate the selection of spawning sites for brown trout. Next to the same spawning areas in 2009 the additionally simulated patches with ‘high’ and ‘very high’ values of HSI_{spawn} were selected for spawning in 2010 as it is indicated in Fig.D.2.28 for the two counted redds upstream of SP3 and for the patchy characteristic downstream of SP2. But during 2010 not all redds were located in suitable areas. Between SP1 and SP2 natural redds were found, although these areas were simulated to be not suitable. These redds however, are very close to patches having a ‘high’ and a very ‘high’ suitability and the discrepancies are most likely due to inadequate numerical modelling of the sediment characteristics during flooding which is not able to identically reproduce the particle size distribution on a very local scale. Based on the analysis of the simulated habitat qualities for spawning and the comparison to mapped natural redds it can be stated that the predefined fuzzy-sets and fuzzy-rules well approximate the habitat requirements of brown trout for the selection of spawning sites

Supply of spawning habitats

A further analysis, including an integrated evaluation of the entire study site is performed using the normalized areas of equal HSI_{spawn}. Fig.D.2.29 illustrates the time-series of areas of equal HSI_{spawn} for the period after artificial flooding to the end of the spawning periods in 2009 and 2010.

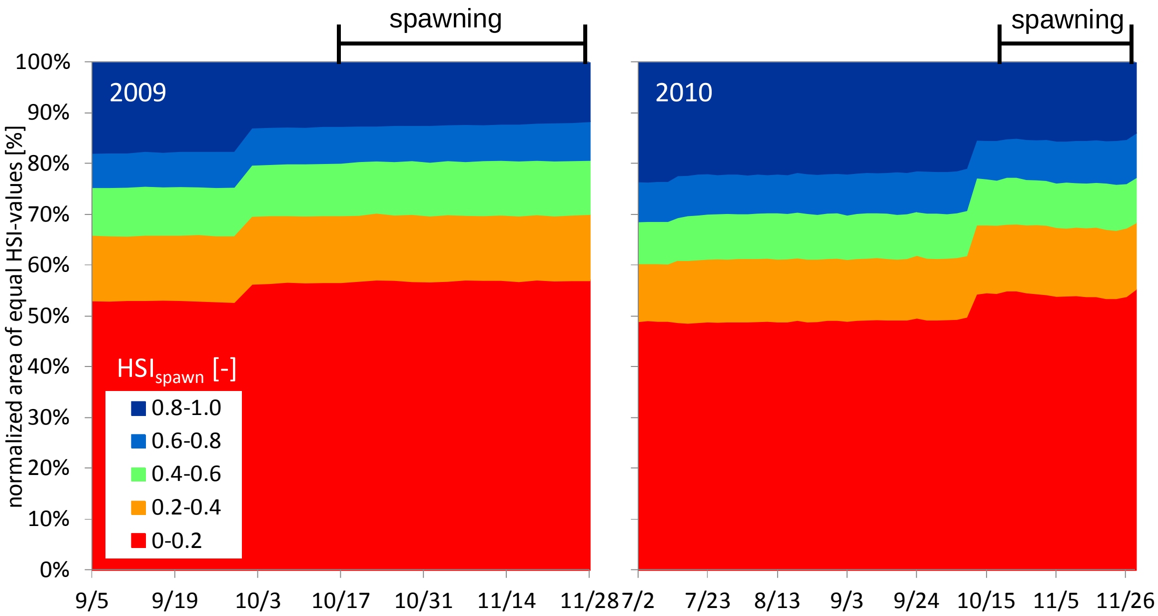


Figure D.2.29: Time-series of normalized areas of equal HSI_{spawn} from the period after artificial flooding to the end of the spawning periods in 2009 and 2010

While during 2009 the time period between artificial flooding and spawning encompasses 85 days it is increased to 150 days for 2010. In both diagrams the change of the flow regulation at the beginning of October (1.44 m³/s to 0.68 m³/s) is indicated by a reduction of the available areas for spawning by approximately 7 %. The aforementioned steadiness of input variables is confirmed by the relatively stable areas with equal HSI_{spawn} in Fig.D.2.29. In a comparison of both periods it can be stated that more areas of 'very high' suitability (15 %) are simulated for the period 2010 compared to 2009 (12 %). Considering all values of HSI_{spawn} >0 a total percentage of 43 % of the study site is found in 2009 where spawning is possible, while it is 51 % in 2010. Although the timing of the artificial flood in 2010 was significantly earlier when compared to 2009, slightly better spawning conditions were simulated in 2010 which is also confirmed by the higher number of mapped natural redds (43 in 2009, 48 in 2010). Thus it can be stated that no negative effects due to the earlier flooding in 2010 occurred. The areas of equal SSI are visualized in Appendix 8.5 for both spawning periods.

Summary and discussion – spawning habitats

This section aims to discuss the resulting spawning habitat qualities by applying the presented two-stage fuzzy-approach in respect to the uncertainties, the specifications of the fuzzy-model and the ecological significance of the obtained results.

Reliability and uncertainty of input variables

All input variables for both fuzzy-steps are direct results of the numerical model SSIIM2 and consequently the uncertainty and reliability of the input data are purely determined by the quality of the numerical model which is discussed in detail in Chapter D.2.3.2 and Chapter

D.2.3.3. Regarding the simulated percentages of the particle size classes during the spawning period a minor restriction has to be made regarding the capability of SSIIM2 to reproduce the sediment characteristics on a small scale of one or several computational grid cells. This means that a certain sediment characteristic might not be found at the exact same location as in reality but may be close to it. This might be explained by the very high heterogeneous character of the River Spoel and the limited number of sediment samples to describe this sediment heterogeneity. In terms of the selection of spawning sites this is negligible as long as the characteristic patch is available because a spawning fish searches the river bed for appropriate habitats and is not dependent on a certain location. For the hydrodynamics variables water depth and flow velocities a low uncertainty is assumed given to the calibration of the hydrodynamic model.

Two-stage fuzzy-model to simulate SSI and HSI_{spawn}

The fuzzy-set used to calculate the sediment spawning index (SSI) for each particle class consists of three membership functions with relatively high overlapping ranges to consider an increasing fuzziness of the approach given to limited information in literature about required percentages for the particle size classes and the uncertainties of morphodynamic modelling. The sets for the hydrodynamic variables consist both of five membership functions given to the excellent knowledge regarding the hydrodynamic preferences. The fuzzy-rules were again specified by the biologist Johannes Ortlepp to assure the highest expertise.

In contrast to common habitat modelling approaches for spawning habitats the two-stages of the fuzzy-approach allows for a more precise formulation of habitat requirements whereby the intermediate result (SSI) provides highly valuable information about the sediment characteristics for spawning. Particularly the unsteady simulation of classified particle size distributions allows for a consideration of requirements on the amount of fine sediments or the maximum movable particle size during redd digging which cannot be considered using single or static sediment indices.

Based on the analysis of spawning habitat quality, it is found that in both spawning periods (2009, 2010) about 45% of the study site are characterised by $HSI_{spawn} > 0$. However, when considering only the ‘high’ and ‘very high’ HSI-classes, the suitable areas are reduced in 2009 to 19 % and in 2010 to 23 %. Although this differences are marginal, this outcome is confirmed by the total number of redds. In 2009 a total of 43 redds were counted while in 2010 the number counted increased slightly to 48. In order to investigate the effects of artificial flooding in the River Spoel, the two investigated periods (2009, 2010), with different occurrence of the artificial flooding before the spawning season, are compared and it is concluded that the longer period in 2010 between artificial flooding and spawning season had no negative effects on spawning habitat quality.

The high quality of simulated HSI_{spawn} is not only confirmed by the comparison with mapped spawning redds but also by the areas that are simulated as not suitable because spawning fish avoid these areas for spawning. However, without the exact dimensions of each natural redd only a visual comparison (Fig.D.2.28) is feasible. There are several habitat variables (listed in Tab.A.2.4) which are not considered in the two-stage fuzzy-approach. One aspect not considered in habitat modelling is the availability of cover which could be easily implemented into the fuzzy-approach of CASiMiR. According to the local fish biologists the availability of cover does not play a significant role in the River Spoel due to the lack of predators and the constant flows during spawning. The interstitial factors are implemented in the incubational life-stages where they have a significantly higher relevance compared to the spawning stage. Finally, factors like competition among spawning fish and superimposition - concerning the available space of spawning areas - are not considered in the fuzzy-approach, although the population of brown trout is near the maximum capacity and competition for the most suitable habitats during the spawning process and superimposition are likely in the River Spoel. Nevertheless, according to the obtained results, the actual used spawning sites are well approximated for the two different spawning periods, confirming the functionality of the approach.

Ecological significance of simulated HSI_{spawn}

As the first life-stage to be considered during the reproduction of brown trout, the simulation of spawning habitat quality is of high importance in the modelling framework as only the areas with values of HSI_{spawn} larger than zero are used for the further modelling steps. Further the availability of suitable spawning areas can be considered as a precondition for a successful reproduction of brown trout (Chapter A.2.2.5). The available particle size distributions during spawning are a result of the natural dynamic (or non-dynamic) behaviour of rivers before spawning reflecting the frequency of bed alterations with consequential sorting processes in all dimensions (Chapter A.2.2.1). For the River Spoel this was investigated by analysing the time periods before artificial flooding until the end of the spawning period. The spatial and temporal variations of SSI and HSI_{spawn} in particular allow for a dynamic assessment of the influence of artificial flooding before the spawning period. Given the excellent agreement of simulated and actual used spawning areas, the functionality of the approach is proved and hence, it is concluded that also the ecological significance is appropriately represented by the simulated values of HSI_{spawn}.

D.2.5.2 Incubation habitats

The next period considered in the multi-step habitat modelling framework is the incubation period including the life-stages eyed-eggs, hatching and larvae. According to Crisp (1996) the incubation phase encompasses the period from mid-November to mid-April which is further subdivided into periods for the eyed-egg stage, the hatching stage and the larval stage (Appendix 8.1). To simulate the life-stage specific habitat suitability (HSI_{egg}, HSI_{hatch} and HSI_{larv}) the two-stage fuzzy-approach described in Chapter C.1.4 is applied using the fuzzy-sets and fuzzy-rules specified in Appendix 2.1 and 2.7. Therefore the simulation of IHS-values are used as a first fuzzy-step (Chapter D.2.4) while in a second fuzzy-step the IHS-values are combined with occurring bed level changes and the direction of the vertical hydraulic gradient (Chapter C.1.4).

Input data – incubation habitat

In addition to the interstitial habitat suitability for the incubational life-stages (Chapter D.2.4) the bed level changes are used as a habitat describing variable due to the fact that all life-stages are endangered of being flushed out from the protecting gravel-framework of the river bed if the depth of erosion reaches typical egg burial depths. The incubation habitat is further determined by the mixing processes between groundwater and surface water which is indicated by the direction of the vertical hydraulic gradient. Limiting conditions occur in upwelling areas where groundwater is infiltrating into the interstitials and drastically reduce the supply of oxygen to eggs and larvae. Fig.D.2.30 shows the spatial distribution of habitat variables used for determining the HSI_{egg}, HSI_{hatch} and HSI_{larv} for the incubation period 2009/2010.

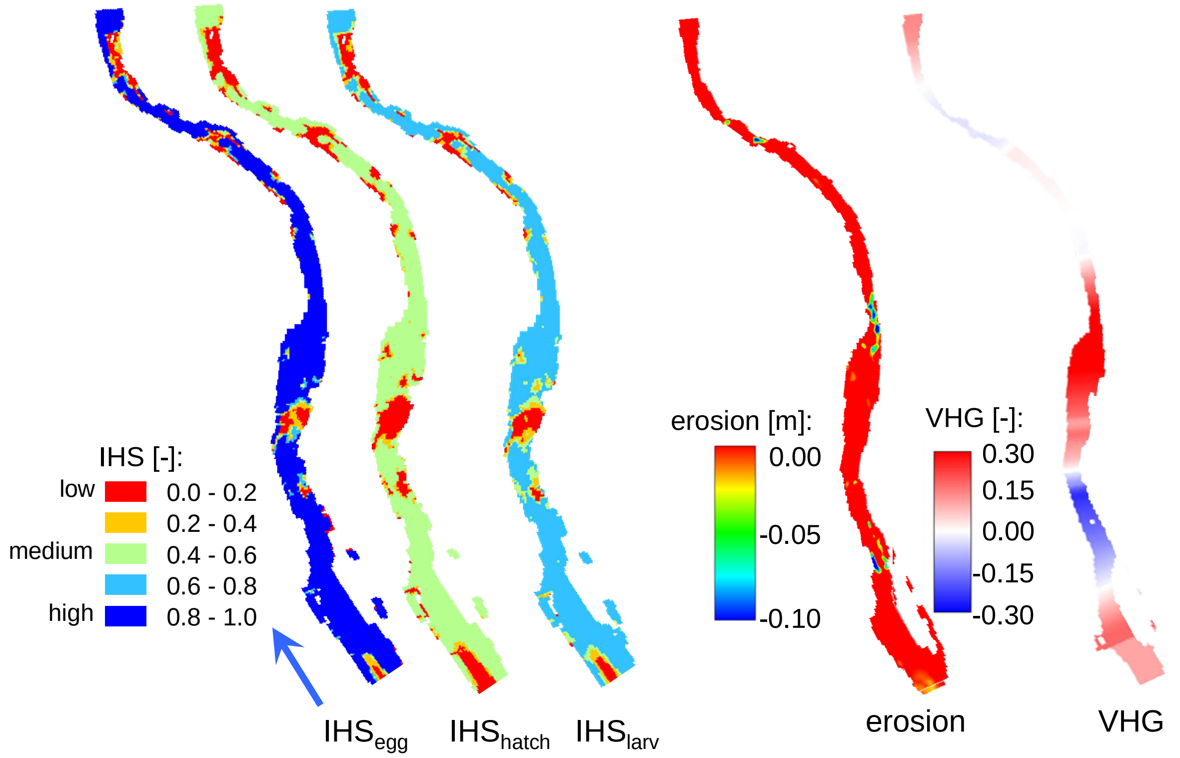


Figure D.2.30: Spatial distribution of habitat variables to simulate the habitat suitability index for the life-stages eyed-eggs, hatching and larvae (HSI_{egg}, HSI_{hatch}, HSI_{larv}) in the incubation period 2009/2010

The description and interpretation of the simulated IHS-values during the incubational life-stages is found in Chapter D.2.4. For the variable bed level change, in terms of erosion, only minor influences on HSI_{egg}, HSI_{hatch} and HSI_{larv} are assumed due to the flow regulation of 0.68 m³/s in the River Spoel. Although the maximum of simulated erosions is -0.12 m, it does not affect the HSI-values during incubation as this erosion is outside of the spawning areas. The mean erosion depth is less than -0.01 m and particularly in the spawning areas erosion is even lower. These relatively stable river bed conditions are roughly confirmed by the buried egg capsules that were not displaced during the incubation periods, the capsules are however significantly heavier compared to single eggs or larvae. Although the bed level changes in the River Spoel are of minor relevance, it is not neglected as a habitat variable because it describes an absolute exclusion criterion for successful reproduction and may lead to 100 % mortality if the erosion reaches typical egg burial depths (Chapter C.1.4.1).

The vertical hydraulic gradient is assumed to be a temporally static habitat variable over the whole incubation period. This assumption is reasonable given to the regulated flow conditions. However, variations of the vertical hydraulic gradient may be induced by precipitation events that have an effect on the groundwater level. The values for the vertical hydraulic gradient in Fig.D.2.30 are obtained by the calibration of the semi-empirical approach of Schaelchli (1993) for simulating the infiltration masses. However, as specified in the fuzzy-sets in Appendix 2.7, the values of the gradient are of minor importance as only the direction of the vertical hydraulic gradient is considered. The direction of the vertical hydraulic gradient, indicating up- and downwelling zones, affects the resulting HSI-values only in upwelling zones which are located in the River Spoel at the end of the riffles in the study site (downstream of SP1 and upstream of SP3). The spatial distribution of input variables for the incubation period 2010/2011 is shown in Appendix 9.1.

Results – incubation habitat

The obtained simulated values for HSI_{egg}, HSI_{hatch}, and HSI_{larv} are based on the fuzzy-sets and fuzzy-rules presented in Appendix 2.1 and 2.7 which are applied in both incubation periods (2009/2010, 2010/2011). The obtained results are presented in their spatial distribution, in their time-series on specific locations and in their habitat supply.

<u>Spatial distribution of HSI-values during incubation</u>

The first presented results of the two-stage fuzzy-approach are the spatial distributions shown in Fig.D.2.31. Visualized are the most limiting habitat conditions in each life-stage for both incubation periods (2009/2010, 2010/2011).

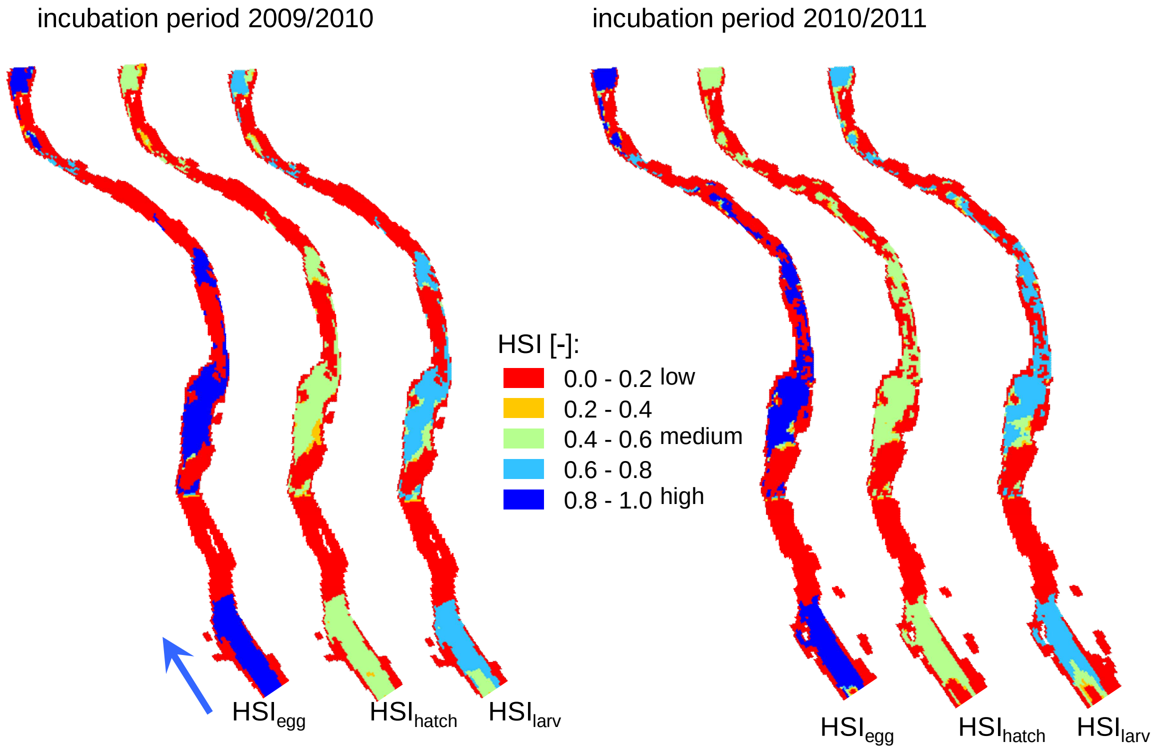


Figure D.2.31: Spatial distribution of habitat suitability index for the life-stages eyed-egg, hatching and larvae (HSI_{egg}, HSI_{hatch} and HSI_{larv}) in both incubation periods (2009/2010, 2010/2011)

It is worth noting that the fuzzy-model to simulate the HSI-values during incubation is only applied in areas that are useable for spawning ($HSI_{spawn} > 0$), because only in those areas the values of HSI_{egg}, HSI_{hatch} and HSI_{larv} are relevant in terms of the reproduction of brown trout. A comparison of the obtained HSI-values for the life-stages during incubation (Fig.D.2.31) to the corresponding IHS-values (Fig.D.2.24) indicates that the quality of incubation habitats is largely determined by the IHS-values, except in areas that are not suitable for spawning (HSI_{spawn}=0). For the River Spoel this is relatively simply explained by the fact that erosion in the spawning areas is negligible and the vertical hydraulic gradient only has an impact on HSI-values in upwelling zones which are found outside of areas with HSI_{spawn}>0. Following this argumentation, the HSI-values visualized in Fig.D.2.31 are exclusively determined by the permeability, the interstitial temperature and the hyporheic respiration (first fuzzy-step). This leads to lowest limitations during the eyed-egg stage, highest limitations during the hatching stage and an intermediate limitation during the larval stage. Regarding the spatial distribution a low spatial variability is simulated within the spawning areas itself that are predominantly characterised by a single HSI-class. For the hatching and larval stage this is explained by the selection of the most critical stage during each life-stage which is achieved for critical temperatures < 3°C and lowest permeability values. For the eyed-egg stage the uniform HSI-distribution of ‘very high’ HSI-values is reliable, as no habitat variables are in a critical range (see also Chapter D.2.4). Comparing both reproduction periods no relevant differences are recognizable in Fig.D.2.31 except of the different areas where HSI_{spawn} is larger than zero.

Temporal variation of HSI-values during incubation

According to the negligible effects of the habitat variables bed level change and direction of vertical hydraulic gradient, the dynamically varying HSI-values would be almost identical to the simulated IHS-values shown in Fig.D.2.25. In order to consider the fact that previously simulated limited habitat conditions cannot be compensated by more suitable conditions to a later time-step, a comparison after each time-step is implemented to determine if the presently computed HSI-values are higher or lower compared than the previously determined values. Fig.D.2.32 (B) shows the time series of HSI_{egg}, HSI_{hatch} and HSI_{larv} for the artificial redds R2, R5 and R9 of the incubation period 2009/2010. For orientation Fig.D.2.32 (A) shows the spatial distribution of HSI-values at the end of hatching stage. The time-series for all artificial redds in both incubation periods are shown in Appendix 9.2.

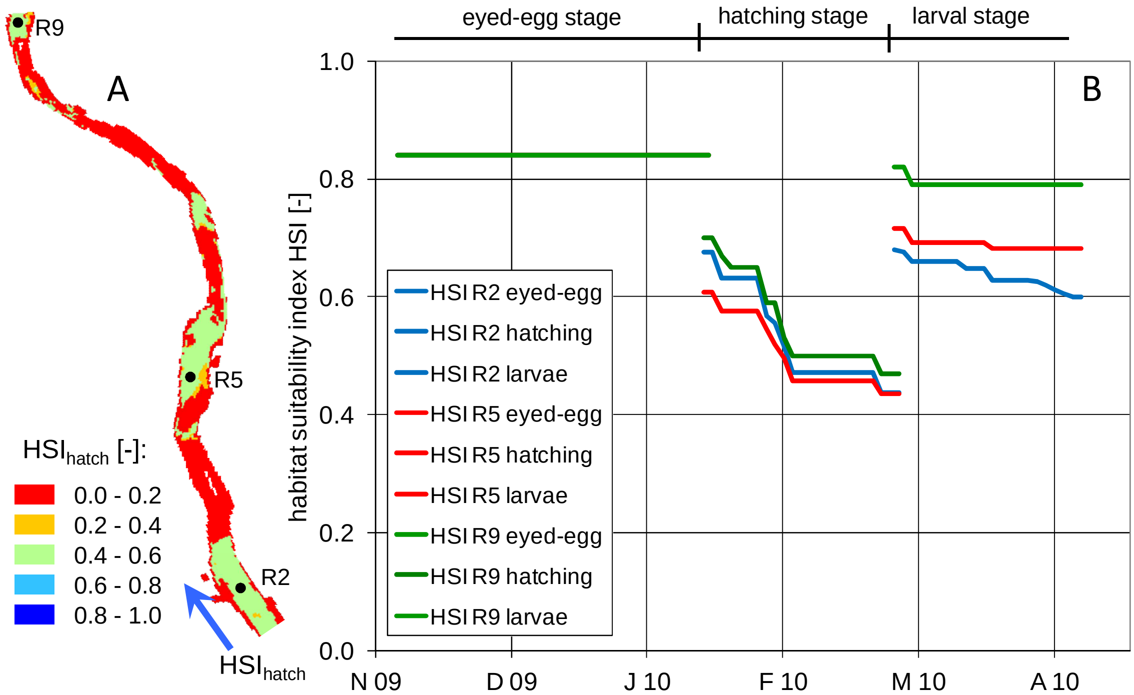


Figure D.2.32: Temporal variations of simulated HSI-values (HSI_{egg}, HSI_{hatch}, HSI_{larv}) during the incubation period 2009/2010 in the artificial redds R2, R5 and R9

It is determined that the habitat suitability for the eyed-egg stage is not limiting the reproduction of brown trout in the River Spoel as the values of HSI_{egg} for the redds R2, R5 and R9 are exclusively within the ‘very high’ range. The obtained results for the hatching stage are found to be significantly different. At the beginning all redds are within the ‘high’ range but become significantly reduced to the ‘medium’ HSI-class. This reduction is caused by the interstitial temperature that reaches a critical limit and thus affects the HSI-values. Not only can the effect of temperature be indicated but also the impact of permeability which is reflected by the lowest HSI-values for R5 and highest HSI-values for R9 for the same interstitial temperatures during hatching. A stronger reduction is observed for R2 and R9 reflecting higher infiltration masses and thus a stronger reduction of permeability when compared to R5 which shows the lowest relative reduction of HSI_{hatch}. The effect of permeability is also indicated in the larval stage. For R9 the permeability is still in the 'high' membership function leading to 'very high' values of HSI_{larv}, while for R5 it is partly 'medium', partly 'high'. The continuous decrease of R2 is a result of the continuously increasing degree of the membership to the 'medium' class of permeability (see also Chapter D.2.4). While the redds figured in Fig.D.2.32 result in similar HSI-values for HSI_{egg} and HSI_{hatch} with only a low variability for HSI_{larv}, the overall result considering all redds in the study site of the River Spoel indicates a high variability (Appendix 9.2). For instance, during the incubation period of 2009/2010 the artificial redds R6 in SP2 have considerably lower HSI-values for all life-stages and in SP3 only R9 is characterized by 'high' and 'medium' HSI-values while R7 and R8 are represented by 'low' HSI-values. Because both redds in SP3 (R7, R8) are located closely to the pool area, the numerical model simulated very high infiltration masses for both redds with consequently massive reductions in permeability that lead finally to not suitable habitat conditions during incubation.

It is concluded that principally the temperature and the permeability are equally important for determining the HSI-values during the incubation period in the River Spoel. While the effect of limiting temperature conditions is indicated by the similar reduction of the HSI-values within the hatching stage in each redd, the permeability affects the magnitude of the HSI-values in each redd. The hyporheic respiration has only a small effect and the parameters of the second fuzzy-step can be neglected, as they are not limiting the HSI-values in the areas where spawning is possible. The highest habitat qualities were found in SP1, whereby SP2 and SP3 show a greater variation within each spawning area. To evaluate the obtained values of HSI_{egg}, HSI_{hatch} and HSI_{larv}, they are compared to the survival rates of hatched individuals obtained by the installation of egg capsules in the river bed (Chapter D.2.2.2).

Comparison of survival rates of hatched individuals obtained from the egg capsules

The buried egg capsules in the artificial redds encompasses the period of eyed-egg stage to hatching. The resulting survival rates are assumed to give a rough verification of the obtained simulation results. As the objective of the modelling approach is not to consider single redds but entire spawning areas, a comparison between the simulated classes of HSI_{hatch} for each spawning area with the mean survival rates in each spawning area is performed (Tab.D.2.4).

Table D.2.4: Comparison of simulated critical HSI-classes during the hatching stage with observed survival rates of hatched individuals

	incubation period 2009/2010		**incubation period 2010/2011**	
	HSI_{hatch} [-]	survival hatching [%]	HSI_{hatch} [-]	survival hatching [%]
SP1	medium/high	71	medium/high	56
SP2	low/medium	74	low/medium	70
SP3	low/medium	72	medium/high	55

The simulated values of HSI_{hatch} in Tab.D.2.4 are given in HSI-classes according to the fuzzy-set specified in Appendix 2.7. Given the overlapping of membership functions each HSI-value belongs to two functions whereby the dominating one is marked by an underline. For the incubation period 2009/2010 the HSI_{hatch} in SP1 belongs equally to the classes 'medium' and 'high', while the values of HSI_{hatch} for SP2 and SP3 belongs mainly to the 'medium' membership function and only partly to the ‘low’ HSI-class. According to the simulated HSI-values best habitat conditions during incubation are found in SP1 while the habitat conditions in SP2 and SP3 are slightly lower on an equal level. This ranking does not fit the ranking of the observed survival rates where the highest survival rates were found in SP2, followed by SP3 and SP1. For the incubation period 2010/2011 a different HSI-value is simulated for SP3, while for SP1 and SP2 similar values as in 2009/2010 are obtained. The observed survival rates are considerably lower compared to 2009/2010 except of SP2 where a similar survival rate was observed. Again the ranking of the simulated HSI-values does not reflect the different survival rates obtained from field-data. However, as all values of simulated HSI_{hatch} are dominated by the ‘medium’ HSI-class a very weak correlation may be seen that relates the ‘medium’ HSI-class to survival rates between 50 % and 70 %.

Although the variance of the averaged values of survival rates is relatively low, high variances are indicated within each spawning area and within each single redd (Appendix 4.10). This high variance might be caused by several factors including diseases, fungal infection, egg handling, egg transport etc. Another aspect affecting the survival rates in 2010/2011 might be the poor weather conditions (-18 °C) during installation of the egg capsules. Given these multiple factors the variations of the observed survival rates cannot purely traced back to varying abiotic conditions. This greatly restricts the comparability and verification method. Thus, the weak correlation of the comparison in Tab.D.2.2 not necessarily reflects the model quality.

Supply of incubation habitat

The analysis of the incubation habitat supply in the form of areas of equal HSI-values (Fig.D.2.33) is only performed in the areas where values of HSI_{spawn} were previously larger than zero, as the habitat suitability indices during incubation (HSI_{egg}, HSI_{hatch}, HSI_{larv}) are only relevant in areas where spawning is possible. Therefore the areas of equal HSI-values are normalized not on the wetted area but on the area of available spawning habitats. Consequently, information is provided regarding how the areas of equal HSI will change if the total area of HSI_{spawn} > 0 is set to 100 %.

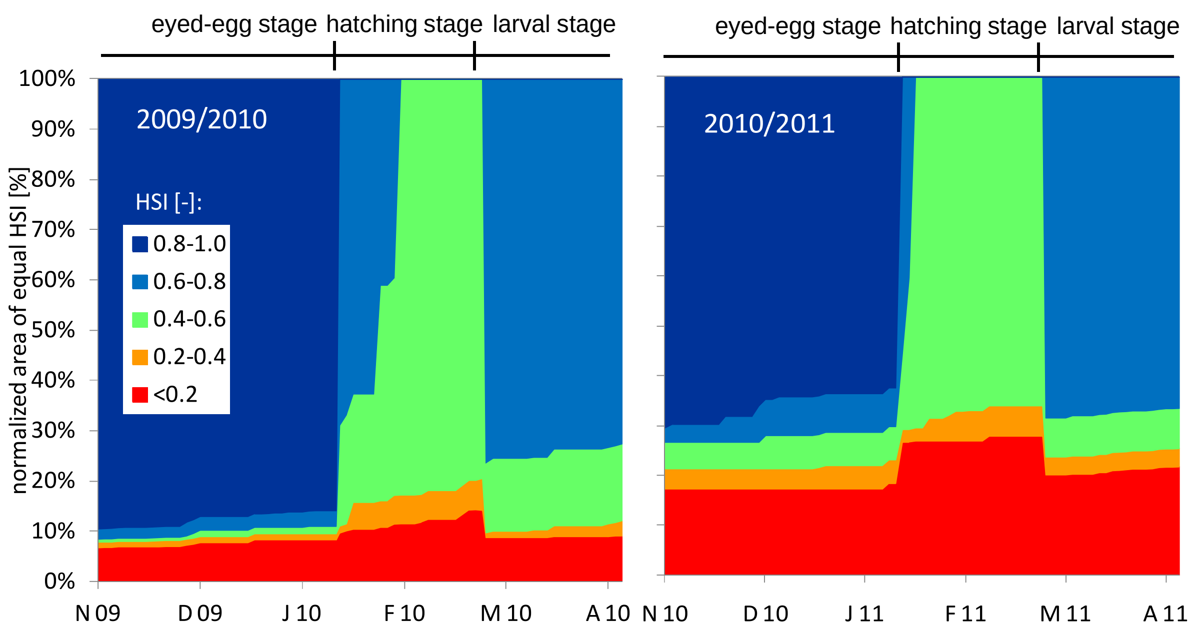


Figure D.2.33: Time-series of normalized areas of equal HSI for the life-stages during incubation (HSI_{egg}, HSI_{hatch}, HSI_{larv}) for both incubation periods (2009/2010, 2010/2011)

Analysing the areas of equal HSI in the spawning areas indicates that during the eyed-egg stage the ‘very high’ values of HSI_{egg} are only slightly reduced from approximately 90 % to 86% in the incubation period 2009/2010 while for 2010/2011 the reduction is 8 %. The habitat supply is most strongly affected during the hatching stage providing ‘high’ HSI-values at the beginning and ‘medium’ values of HSI_{hatch} at the end of the hatching stage. In addition to the overall reduction to the ‘medium’ HSI-class, Fig.D.2.33 indicates also an even stronger increase of the other HSI-classes during hatching compared to the other life-stages during incubation indicating the progressing limiting habitat conditions during the hatching stage. For the larval stage the ‘high’ HSI-class is dominating while for the incubation period 2009/2010 the ‘medium’ value of HSI_{larv} is considerably higher (15 %) when compared to the 2010/2011 period (8 %).

In general, the variations of HSI-values within the spawning areas during the incubation period underlines that the eyed-egg stage has only minor effects regarding the success of reproduction of brown trout, while the strongest impacts occur during the hatching stage which is explained by the highest requirements during the hatching stage and the occurrence of limiting temperatures (< 3°C) in this period. Additionally, an overall reduction of habitat quality is indicated for all life-stages representing the effect of continuously decreasing permeability due to infiltrating fine sediments affecting the HSI-values.

Summary and discussion – incubation habitat

The fuzzy-approach and the corresponding results are discussed in terms of reliability and their ecological significance. As the first fuzzy-step includes the simulation of the interstitial habitat suitability (IHS), it is referred to the discussion in Chapter D.2.4.

<u>Reliability and uncertainty of input variables</u>

In addition to the input variables of the first fuzzy-step used to simulate the interstitial habitat suitability, the bed level change and the direction of the vertical hydraulic gradient are applied in a second fuzzy-step to simulate the HSI-values during the incubation period. The bed level change is directly simulated by the numerical model SSIIM2 and consequently the uncertainty and reliability are purely determined by the quality of the numerical model which is discussed in detail in Chapter D.2.3.2 and Chapter D.2.3.3. In terms of the vertical hydraulic gradient only the direction as an indicator for up- and downwelling processes is used in the fuzzy-approach. The degree of uncertainty is quite high given the fact, that the direction is based only on one measurement of groundwater levels along the study site with a subsequent lateral and longitudinal interpolation that completely neglects any variations in the lateral directions. Additionally the direction of the vertical hydraulic gradient is assumed to be temporally constant which may be correct given the flow regulation, but neglects precipitation events that may have an effect on the direction of the vertical hydraulic gradient (Chapter D.2.2.1). The role of the habitat variables in the second fuzzy-step are of minor relevance as it turned out that in the spawning areas no noticeable erosion occurs and that upwelling areas are only located downstream of the both riffles that are not used for spawning (Fig.2.30). For sites without flow regulation it is highly recommended to combine the numerical model for surface flow with a model of groundwater flow to obtain a high spatial and temporal resolution of vertical hydraulic gradients that are also able to reflect the impacts of variable surface flow conditions on the direction of the vertical hydraulic gradient and consequently the impacts on the incubational habitat quality (see also Chapter A.3).

Two-stage fuzzy-model to simulate HSI_{egg}, HSI_{hatch}, and HSI_{larv}

Although for the River Spoel it was found that the bed level changes and the vertical hydraulic gradient have no apparent effect on the HSI-values simulated by CASiMiR, a brief discussion about the applied fuzzy-sets is presented. Both habitat variables are fuzzified using three membership functions. For the bed level change an impact only occurs for negative bed level changes (erosion) while for the vertical hydraulic gradient the membership functions are specified to consider only the direction of the vertical hydraulic gradient (Appendix 2.7). The available information about the sizes of gradients (that were obtained by the calibration of sediment infiltration process using the semi-empirical approach of Schaelchli (1993, Chapter D.2.3.3)) are not used for describing their effect on the values on HSI_{egg}, HSI_{hatch} and HSI_{larv} given the low resilience due to missing information about the seepage lengths. Also noteworthy is that the influence of surface hydraulics is not considered within this modelling step, as surface hydraulics affect the incubational habitat only through the magnitude of the vertical hydraulic gradient which is the governing variable to determine the amounts of infiltrating surface water or groundwater into the redds. The applied fuzzy-sets and fuzzy-rules were specified in close collaboration with Johannes Ortlepp to assure the application of the indispensable biological expert-knowledge.

Another subject to be discussed is the assumption that a HSI-value within one life-stage cannot increase as a limited habitat condition cannot be compensated by a better habitat condition at a following time-step. The major purpose of this assumption is to consider the effect of limited habitat conditions that will lead to an increasing mortality or to a restricted development which logically cannot be improved by higher habitat conditions that occur afterwards. However, this assumption might be inadequate for critical habitat conditions that occur only for a short duration. If the interstitial temperature falls below the critical threshold for several hours or one day, this does not automatically lead to mortality but might have effects like a reduced growth or fitness which would lead to a pro-longed development (personal comment, Johannes Ortlepp). The applied approach is not able to consider such effects in detail but approximate them by reducing the HSI-values by one HSI-class instead of defining directly a not suitable habitat condition. Nevertheless, the most critical habitat conditions also represent the most valuable information during the incubation period in terms of evaluating the reproduction success.

The obtained results (HSI_{egg}, HSI_{hatch}, and HSI_{larv}) of CASiMiR in the River Spoel are only considered within the spawning areas as only in areas where spawning is possible, an investigation of the incubational habitat is relevant. The obtained HSI-values reflect mostly the impact of the interstitial habitat suitability IHS (Chapter D.2.4) as the habitat variables in the second fuzzy-step are not significant for the River Spoel. Given these outcomes it is concluded that the interstitial temperature and the permeability are equally dominant in determining the HSI-values, while the respiration has a low limiting effect within the spawning areas. Similarly to the restriction formulated for the IHS-values, the exchange processes in the hyporheic interstitial is not fully represented by this approach given the lack of data with regard to the spatially and temporally varying groundwater levels that certainly would increase the appropriateness of the abiotic habitat description. A comparison with the mean survival rates obtained by the egg capsules in the spawning areas SP1-SP3 offered a weak relation to the most critical HSI-values obtained during hatching. However, this relation cannot purely be traced back to varying abiotic conditions due to a very high variation of survival rates in each spawning area as well as in each redd which might be explained by additional factors that are not considered in the approach (disease, egg handling, egg transport etc). Noteworthy are also the ‘low’ habitat qualities simulated in R7 and R8 during the incubation period of 2009/2010 or those in R4 during the incubation period of 2010/2011.

This 'low' habitat quality is not confirmed by the survival rates of the egg. This is mostly explained by the restriction of SSIIM2 to reproduce exactly the sediment characteristics on a very local scale as it is formulated in the discussion part of Chapter D.2.5.1. The 'low' HSI-values of R7 and R8 (2009/2010) are traced back to very low permeability values that occur due to high sediment infiltration close to the pool area. In reality such a high infiltration is not observed in the artificial redds, but the close location of R7 and R8 to the pool area is not sufficiently reproduced in the numerical model SSIIM2 given the lack of a higher numerical spatial discretization in this area.

Ecological significance of simulated HSI_{egg}, HSI_{hatch} and HSI_{larv}

Given that the highest requirements on interstitial habitat occur during incubation, especially during the hatching stage, a high ecological significance for the success or reproduction of brown trout can generally be indicated. However, the incubational development can only be guaranteed if the hyporheic variability is not limiting the abiotic conditions of the interstitial habitats. In the proposed approach the hyporheic variability of the river bed is approximated by the interstitial habitat suitability using the variables permeability, interstitial temperature and the hyporheic respiration in addition to bed level changes and the direction of the vertical hydraulic gradient. With this selection of habitat variables it is assumed to sufficiently describe the abiotic conditions during the life-stages of the incubation period, although not all variables are affecting the incubational habitat quality in the River Spoel. However as all applied variables (except the vertical hydraulic gradient) are considered in a highly temporal and spatial resolution a sufficient replica of the abiotic habitat conditions during the incubation is feasible. These dynamically varying abiotic conditions are contrasted to the different requirements of the incubational life-stages by the habitat model CASiMiR which allows for a detailed interpretation and identification of critical habitat variables at a certain time-step. It is worth noting that the HSI-values themselves cannot directly be related to survival rates obtained in the field as the HSI-values considers only the abiotic environment neglecting the effects of diseases or sub lethal effects that limited growth, strength and fitness of individuals. Based on these aspects it is finally concluded that the approach allows an evaluation of the ecological function of the interstitial habitat regarding the abiotic conditions without considering biotic attributes. The comparison to survival rates in the field might give a first idea to relate the simulated HSI-values to biotic functions, however given the weak resilience of this relation it is recommended to compare the simulated habitat quality in the River Spoel to the habitat conditions of a pristine reference river, which allow for more conclusive assessments of the ecological functionality of the interstitial habitat.

D.2.5.3 Emergence habitats

The last period to be considered in the modelling framework is the emergence period. According to Crisp (1996) emergence occurs between mid-April and mid-May. However, the timing of emergence is strongly determined by the fitness of the larvae and water temperature (Chapter A.2.6). To simulate the habitat suitability index for emergence (HSI_{emerg}) a single-step fuzzy-approach is applied considering the geometric mean diameter, the amounts of particle sizes less than 8 mm and bed level changes as habitat describing variables. The applied fuzzy-sets and fuzzy-rules are presented in Appendix 2.8.

Input data and simulation results– emergence habitat

To simulate HSI_{emerg} totally three parameters are applied in a single fuzzy-step. The geometric mean diameter is used for evaluation of available pore sizes according to the findings of Rubin (1998). The mean geometric particle size may be a poor indicator of available pore sizes for the heterogeneous particle size distributions of the River Spoel as the geometric mean diameter is not very specific in terms of pore sizes. Therefore a second parameter – the fraction of particle sizes < 8mm – is used to evaluate additionally the amount of fine sediments that might block connected pores. Lastly, the bed level change has to be considered to avoid physical damages to the emerging fry due to particles that are in motion as well as for the consideration of unintended displacements.

Spatial distribution of HSI-values during incubation

For the input data used to simulate HSI_{emerg} fairly stable conditions are found over the entire emergence period without evident temporal variations (visualized in Appendix 10.1, 10.2). Therefore only the spatial distribution of input variables and the resulting HSI-values are presented. Fig.D.2.34 shows the input variables and the simulated HSI_{emerg} for the reproduction period 2009/2010 while the obtained results for 2010/2011 are shown in Appendix 10.3.

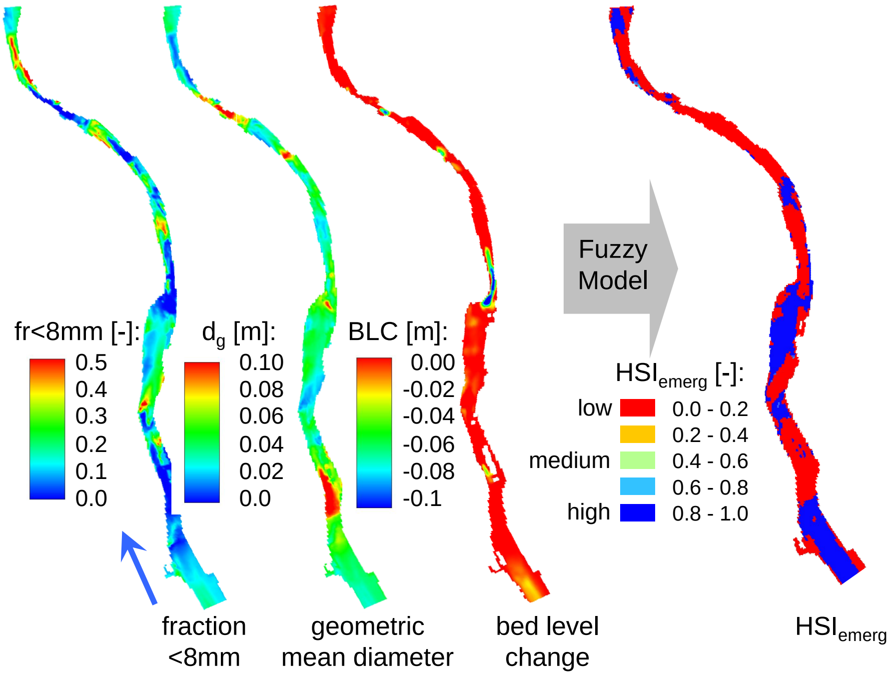


Figure D.2.34: Spatial distribution of in- and output parameter used to simulate the habitat suitability indices for emergence (HSIemerg) in the emergence period 2009/2010

Regarding the description of bed level changes it is referred to the previous chapter (Chapter D.2.5.2) as during the emergence period no bed level changes occurred within the spawning areas that may endanger the larvae by being flushed out of the protecting gravel framework in the river bed or cause physical damage. The percent fraction of particle sizes < 8mm varies in the study site from close to zero to > 50 %. However, the high percentages are only achieved in areas of low bottom shear stresses that are predominantly found in the pool areas. In the spawning areas SP1–SP3 the values vary from 12 % to 23 % which are not limiting the HSI-values in terms of emergence (Chapter C.1.4). The geometric diameter in the spawning areas is always > 0.030 m and exceeds the critical limit of 0.015 m, which leads to no restrictions for emerging larvae.

Combining these abiotic habitat describing variables via fuzzy-modelling to a habitat suitability index leads to ‘very high’ HSI-values for all areas of HSI_{spawn} > 0. Thus, it can be concluded that the emergence from the interstitials of the river bed to the surface water is not at all hindered (based on the investigated habitat variables). Unfortunately it is not possible to verify these outcomes in the River Spoel given the lack of biological data (Chapter D.2.2.2). The results for the reproduction period of 2010/2011 are more or less identical to the reproduction period of 2009/2010. Although there are slight variations in the input parameters, no limiting conditions are achieved resulting in a ‘very high’ HSI_{emerg} for all spawning areas.

Summary and discussion – emergence habitat

Reliability and uncertainty of input variables

While the bed level change and the fraction of particle sizes < 8mm are a direct output of the numerical model SSIIM2, the geometric mean diameter is calculated based on the fractions of each particle size according to Eq.B.2.1. The reliability and uncertainty of all applied habitat variables are purely determined by the quality of the numerical model which is discussed in detail in Chapter D.2.3.2 and Chapter D.2.3.3. The selection of habitat variables to describe the sediment characteristics for emergence is relatively poor and much better descriptors are available. For instance, the porosity which is also a direct output of the numerical model SSIIM2 better reflects the available pore sizes for emergence. However, as the selection of habitat variables depends also on the availability of biological data to determine the habitat requirements, the porosity could not be used as a habitat variable as, so far, no investigations have been performed to investigate the requirements of emergence larvae on porosity. Therefore only the geometric mean diameter and the fraction of particle sizes < 8mm are applicable in the fuzzy-approach.

Fuzzy-model to simulate HSI_{emerg}

The effect of the three habitat variables on the habitat quality for emergence (HSI_{emerg}) are simulated by the habitat model CASiMiR using a single step fuzzy-approach. As for the bed level change the same fuzzy-set is used as was used for the incubation habitat, it is referred to Chapter D.2.5.2. For the other habitat variables - the fraction of particle sizes < 8mm and the geometric mean diameter - three membership functions are applied to describe the occurring values in the study site and the requirements of brown trout. As available information in scientific literature is rare in terms of relating sediment characteristics to purely emergence, it seems to be appropriate to use three membership functions with high degrees of overlap.

The limited applicability of the habitat variables describing the sediment characteristics for emerging purposes has been discussed in the previous section. Another aspect to be discussed is the definition of the particle size to describe the amounts of fine sediments which is specified in this approach with 8 mm. This specification results from the analysis performed by Rubin (1998) who found that larvae are able to move particles sizes up to 6.4 mm as long as they are not consolidated or tilted and from recommendations formulated by Kondolf et al. (2008) to use fractional percentages of particle sizes between 3 mm and 10 mm.

It is noteworthy, that the approach aims not to simulate the effects of drifting or other habitat conditions related to the surface water zone after successful emergence but concentrates purely on the capability of larvae to move through the interstitials of the river bed. Therefore variables describing the hydraulic situation of surface water are not considered. Nevertheless, in the River Spoel it turned out that none of the applied habitat variables are in critical ranges leading to ‘very high’ HSI_{emerg} for all spawning areas in both emergence periods. Hence, the emergence period is not limiting the reproduction success in the River Spoel.

Ecological significance of simulated HSI_{emerg}

As the last part of the reproduction of brown trout, the emergence habitat approximated by the proposed fuzzy-model describes predominantly the sediment characteristics to allow movements of larvae through the interstitials of the river bed and considers possible occurring physical damages due to the transport of particles. The ecological significance of the obtained results are moderate for the following reasons: much better descriptors for the sediment characteristics in terms of defining the pore sizes are available (e.g. porosity). Additionally, the capability of larvae to emerge through the interstitials is strongly determined by the fitness of the larvae (Chapter A.2.2.5) which is completely neglected in the fuzzy-approach. This includes the effects of pro-longed development due to poor incubational habitat conditions resulting in larvae that are too weak to execute the emergence process successfully. Finally, the connection of pores to provide interstitial pathways is not considered in the approach as no numerical model is able to simulate the connectivity of available pores in the river bed. This however might not affect the emergence drastically as larvae are able to move particle sizes up to 6.4 mm (Rubin, 1998).

D.2.6 Simulation of reproduction habitat suitability (RHS)

The aggregation of the time-dependent HSI-values to reproduction habitat suitability (RHS) concludes the multi-step habitat modelling framework and addresses the last part of hypothesis 3. The objective of the aggregation is to provide an integrated result that is based on the spatial and temporal varying habitat conditions as well as allowing a quick identification of critical habitat conditions of available reproduction habitats of brown trout.

D.2.6.1 Input data – Reproduction Habitat Suitability (RHS)

The required input data to calculate the reproduction habitat suitability are the intermediate results of HSI-values obtained from the previous modelling steps of the associated life-stages. Fig.D.2.35 provides the time-series of all HSI-values during the reproduction period of 2009/2010 for the artificial redds R2, R5 and R9. Appendix 11.1 and Appendix 11.2 present the time-series of HSI-values for all artificial redds for both reproduction periods (2009/2010, 2010/2011).

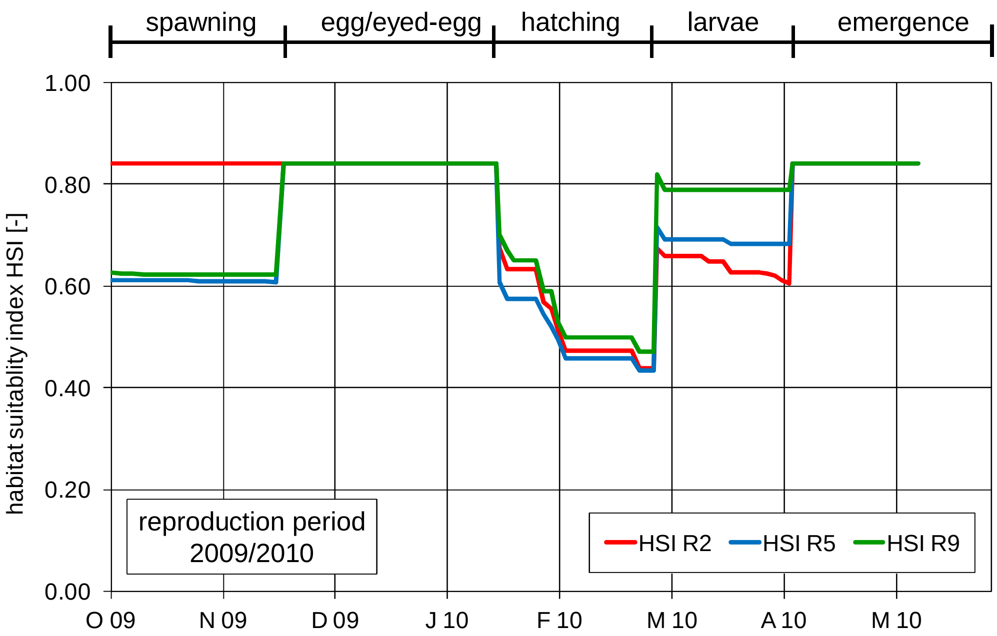


Figure D.2.35: Time-series of simulated HSI-values (HSI_{spawn}, HSI_{egg}, HSI_{hatch}, $HSI_{larv,}$ HSI_{emerg}) during the reproduction period 2009/2010 in the artificial redds R2, R5 and R9

Fig.D.2.35 indicates for the artificial redd R2 that the spawning stage, the eyed-egg stage and the emergence stage are not affecting the success of reproduction given to ‘very high’ HSI-values. Only during the hatching stage the HSI-values are reduced to a ‘medium’ habitat quality. Although the larval stage of R2 is marked by the lowest HSI-values it is still a ‘highly’ suitable habitat. For R5 and R9 the spawning habitat quality is lower compared to R2 but still in a ‘high’ HSI-class while the eyed-egg stage and the emergence stage are not limiting the reproduction. During the hatching stage the HSI-values show a similar decline as the HSI-values for R2. The visualization in Fig.D.2.35 also considers the effect that limited habitat conditions cannot be compensated by better habitat conditions at a later time-step. However, this is only considered within each life-stage as the habitat conditions of the following life-stage have to be additionally evaluated as life-stages are not necessarily interconnected. For instance, if the spawning habitat quality is ‘medium’ then a fish might use this suboptimal habitat for reasons of competition or limited available space. Similarly, the habitat conditions of the larval stage are described for the actually hatched fish and are assumed to be not interrelated to the HSI-values of the hatching stage. Again it is important to notice, that the objective is not to simulate survival rates but the dynamically changing abiotic habitat conditions. The illustration of habitat dynamics over the entire reproduction period in 2009/2010 allows a quick and easy identification of bottlenecks (limited habitat conditions) that affect the success of the reproduction of brown trout in the River Spoel. The time-series of simulated HSI-values themselves present extremely valuable information for analysing the reproduction success on specific locations of the study site.

An integrated result over the whole study is provided by the visualisation of the habitat supply expressed by the normalized areas (wetted area) of equal HSI-values (Fig.D.2.36). The habitat supply for the period 2010/2011 is shown in Appendix 11.3.

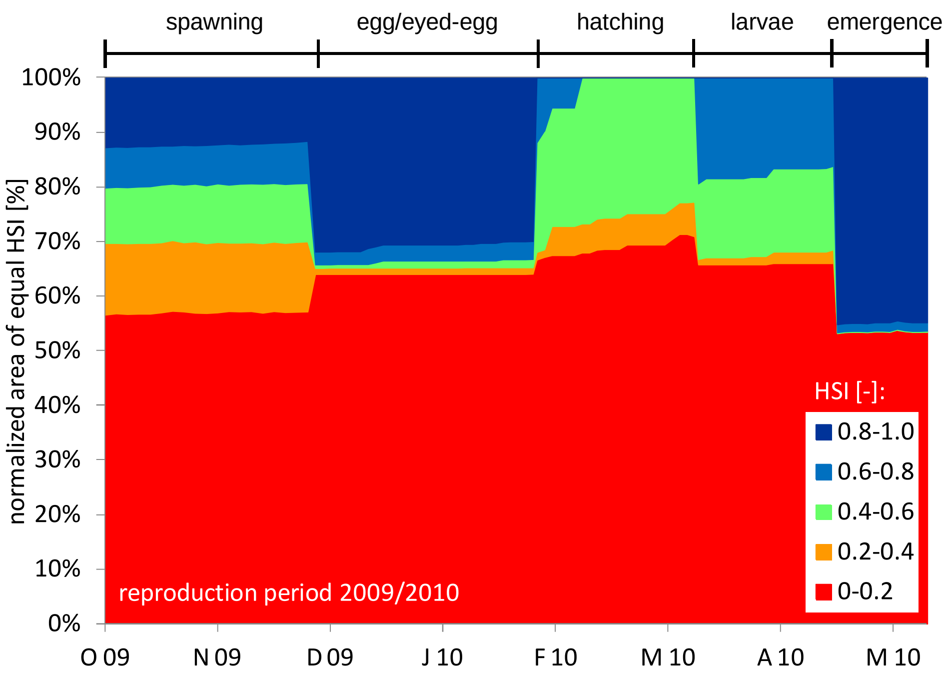


Figure D.2.36: Time-series of normalized areas of equal HSI-values for the life-stages during the reproduction period 2009/2010 (HSI_{spawn}, HSI_{egg}, HSI_{hatch}, HSI_{larv}, HSI_{emerg})

The temporal variation of the normalized areas of equal HSI-values shows principally a similar picture as Fig.D.2.35, but is not focused on specific locations of the study site but considers in an integrated way the entire study site. While for the spawning, the hatching and the larval stage a heterogeneous distribution of HSI-values is indicated, the eyed-egg and emergence stage are predominantly represented by 'very high' HSI-values, except of areas where spawning is impossible. This underlines the limited effect on reproduction success of the eyed-egg and emergence stage. To obtain an overall result, the simulated HSI-values are aggregated to the reproduction suitability index which is presented in the following section.

D.2.6.2 Results - Reproduction Habitat Suitability (RHS)

The aggregation to a reproduction habitat suitability (RHS) of the dynamically simulated HSI-values aims to provide a summarized result of the previously simulations that are performed for each life-stage during reproduction with the habitat model CASiMiR. Therefore the RHS-values contain the summarized effects of all varying abiotic conditions during the investigated period on the habitat quality for the reproduction of brown trout. The HSI-values of each life-stage are aggregated by Eq.C.1.15 considering a multiplicative linkage of the minimum HSI-value in each life-stage.

Spatial distribution of simulated RHS-values

Eq.C.1.15 is performed for each element of the computational grid resulting in a map of RHS-values as it is illustrated in Fig.D.2.37 for both reproduction periods (2009/2010, 2010/2011). The resulting RHS-values are classified according to the verbal classification of HSI-values. It is important to note that the 'very high' RHS-class represents the highest RHS-values obtained in the study site which is 0.25. Therefore the verbal expression 'very high' reflects neither a very high survival rate nor the theoretically best possible habitat conditions.

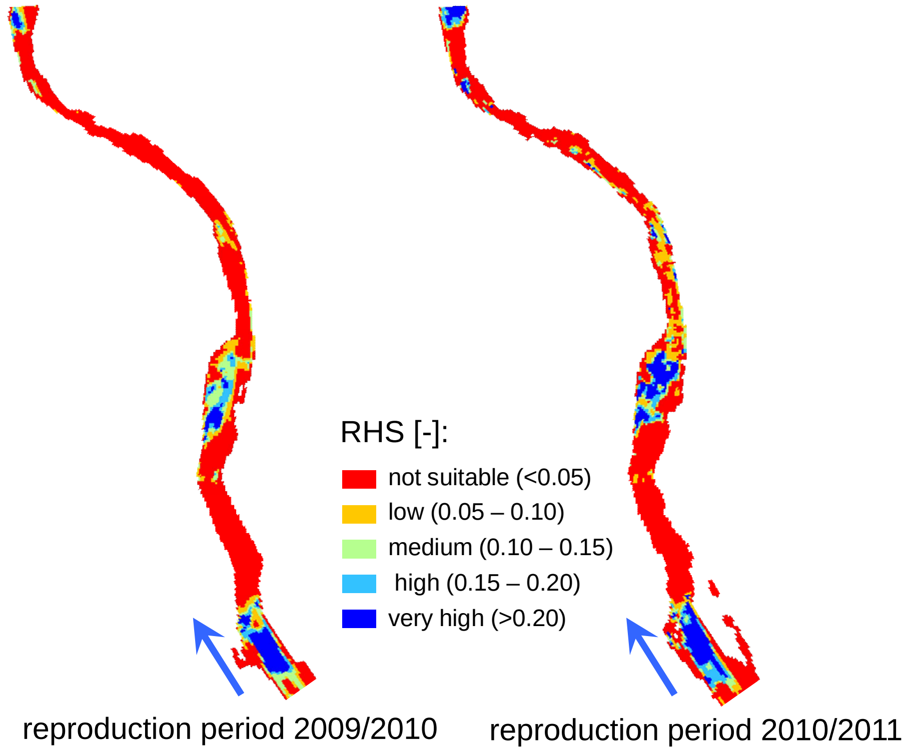


Figure D.2.37: Spatial distribution of simulated reproduction habitat suitability for both reproduction periods (2009/2010, 2010/2011)

The visualization of the spatial distribution of RHS-values provides an overview of the quality of the various habitats for reproduction purposes of brown trout. This allows a quick identification of locations with 'high', 'medium' or 'low' reproductive habitat conditions. The relatively low RHS-values in a range of 0 to 0.25 are caused by the multiplicative linkage of

HSI-values. For example, a RHS-value of 0.25 corresponds to a minimum of HSI-values of approximately 0.75 for all life-stages. The highest possible RHS-value would be 0.42 (0.84^5), which according to the specified fuzzy-set of HSI-values is the highest possible HSI-value (see also Chapter C.1.4). However, in reality such a value is not very likely to be achieved, as this would require optimal habitat conditions over the whole reproduction period. Therefore it was decided to use the min-max values in the study site to classify the range of 'low' to 'very high' RHS-values. This allows additionally for a proper representation of the spatial heterogeneity of RHS-values. Fig.D.2.37 indicates areas with 'very high' RHS-values in both reproduction periods in the spawning areas SP1-SP3. The RHS-values differ in SP2, where significantly more areas of the 'very high' RHS-class are available during the reproduction period 2010/2011, while in 2009/2011 the reproduction habitat is largely characterised by 'medium' and 'high' RHS-values. The additional spawning areas in 2010/2011 (downstream of SP2) are mainly characterised by a 'low' reproduction habitat quality except for single patches that are highly suitable for reproduction purposes. SP3 is marked by 'very high' RHS-values in both reproduction periods, whereby the area in 2010/2011 is considerably larger than in 2009/2010. To integrate the available reproduction habitats in the River Spoel the supply of reproduction habitats is evaluated using the areas of equal RHS-values as it is presented in the following section.

Supply of reproduction habitat

Fig.D.2.38 presents the supply of reproduction habitats normalized by the available spawning area for both reproduction periods (2009/2010, 2010/2011).

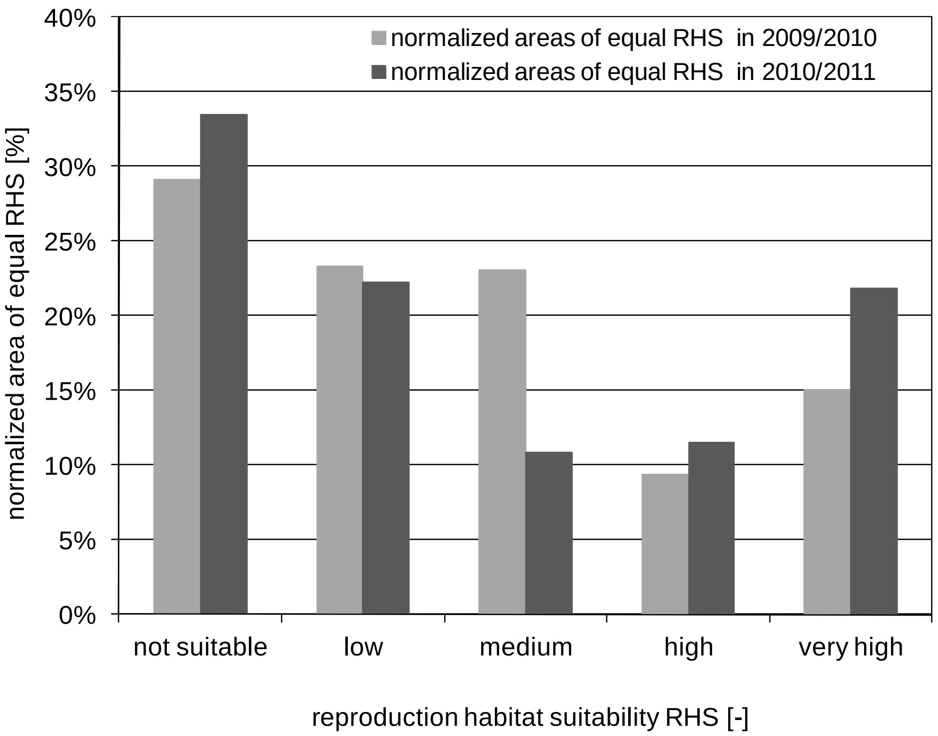


Figure D.2.38: Normalized areas of equal RHS-values for both reproduction periods (2009/2010, 2010/2011)

Analysing the supply of reproduction habitats it shows that for both reproduction periods approximately 30 % of areas where spawning is possible ($HSI_{spawn} > 0$) are not suitable for reproduction purposes while about 23 % have only a 'low' suitability. However, a significant difference is indicated for the RHS-classes of ‘medium’ and ‘very high’. While for the reproduction period 2009/2010 considerably larger areas are in the ‘medium’ RHS-class, the reproduction period in 2010/2011 provides wider areas in the RHS-class ‘very high’. To finally evaluate the overall habitat supply for reproduction the weighted usable area (WUA) according to Eq.A.3.13 is calculated and normalized by the spawning area. The WUA-value evaluates all areas with a RHS > 0 and weights them by the simulated RHS-value. Interestingly for both reproduction periods a normalized WUA-value of 0.13 is determined leading to the final conclusions that the habitat supply is equally affected during both reproduction periods. In Fig.D.2.38 these outcomes can be interpreted by the value of the area of ‘medium’ RHS-class in 2009/2010 which significantly exceeds the values of 2010/2011 compared to the degree that the area of the ‘very high’ RHS-class in 2010/2011 exceeds the values of 2009/2010. However, it is noteworthy that for the reproduction period 2010/2011 more spawning areas ($HSI_{spawn} > 0$) are available, consequently the total area of habitat supply is higher for the reproduction period 2010/2011. This conclusion is confirmed using the WUA-values without the normalization on available spawning areas resulting in a habitat supply of 335 m² for the reproduction period 2009/2010 and in a habitat supply of 378 m² for the reproduction period 2010/2011. Thus 10 % more reproduction habitats are available in 2010/2011. Finally it can be stated – based on these outcomes – that the earlier artificial flooding in 2010, which provides more time for sediment infiltration process affecting the sediment characteristics, has no negative impact on the supply of the reproduction habitat.

D.2.6.3 Summary and discussion – Reproduction Habitat Suitability (RHS)

The aim of aggregating the simulated habitat dynamics for each life-stage of the reproduction habitat to a reproduction habitat suitability (RHS) is to provide a summarized result including the impact of spatial and temporal variability of the abiotic conditions on the success of the reproduction of brown trout. As the final result of the multivariate fuzzy-logic model framework, the RHS-values are discussed according to the aggregation method and the interpretation of RHS-values. Regarding to the ecological significance it is referred to Chapter D.2.7 where the ecological significance of the entire habitat modelling framework is explained.

Multiplicative linkage of minimum HSI-values in each life-stage

One aspect to be discussed is the multiplicative linkage of the minimum HSI-values during each life-stage of the reproduction period. The application of the minimum HSI-values is reasonable, as the most critical habitat conditions have to be considered for the evaluation of the entire reproduction habitat. However, similarly to the argumentation for simulating the HSI-values for the life-stages, the duration of limited habitat conditions plays a significant role for the reproduction success as a short time of limited condition can be tolerated within the life-stages of reproduction. In the River Spoel this is predominantly relevant for the incubation period and is considered in the fuzzy-rules by reducing the HSI-values by one level instead of defining a not suitable condition. In doing so, shortly occurring limited conditions are compensated and thus, it is assumed that the minimum HSI-values are the most appropriate approximation to consider the limited habitat conditions during reproduction. In contrast, the multiplicative linkage does not allow for a compensation of the minimum HSI-values obtained in each life-stage. This is also reasonable as, for instance, if the incubation habitat quality is ‘low’ the RHS-value cannot achieve a higher value than ‘low’ due to a ‘very high’ emergence habitat. For these reasons it is assumed that the multiplicative linkage of minimum HSI-values in the life-stages during reproduction is an appropriate method to obtain a summarized result of the entire modelling framework.

Interpretation of RHS-values

For interpretation of the obtained RHS-values it is important to note that the verbal classification of RHS-values from ‘low’ to ‘very high’ orientates on the occurrence of min-max values in the River Spoel and encompasses values between 0.00-0.25. Therefore, the verbal expression ‘very high’ reflects neither a very high survival rate nor the best possible habitat conditions which would be achieved for a value of approximately 0.4 (RHS_{max}=0.84[5]). However, in reality such a value is not very likely to be achieved, as this would require optimal habitat conditions over the whole reproduction period. The classification according to the occurring min-max values in the study site has the advantage to allow for a proper representation of the spatial heterogeneity of RHS-values.

The main strength of the RHS-values lies in the aggregation of HSI-values obtained for the single life-stages enabling the presentation of RHS-values in the form of spatial distributions or in the form of habitat supply. This allows for a quick overview of the obtained results and is ideally suited for comparing the effects of different abiotic conditions on the reproduction habitat. This includes, for instance, the reproduction period of different years to allow an assessment of the long-term development of reproductive habitats but also to investigate management scenarios like variations in number, timing, magnitude and duration of artificial flooding. A more detailed result is provided using the time-series of HSI-values or the areas of equal HSI over the whole reproduction period as these results explicitly includes both the temporal and spatial variations of habitat dynamics without aggregating them to one single value. This allows identifying the timing, location and duration of habitat bottlenecks. Moreover, an interpretation of the HSI-values allows for an identification of the responsible abiotic variables leading to critical habitat conditions which provides highly valuable information for planning mitigation scenarios.

Intermediate summary and conclusion

Analyzing the obtained RHS-values in the spawning areas shows that for both reproduction periods approximately 50 % of available spawning areas that are not suitable for reproduction or have a ‘low’ RHS-value, while the other 50 % have RHS-values in the range of ‘medium’ to ‘very high’. In 2009/2010 more areas are assigned to the ‘medium’ class while in 2010/2011 more areas are assigned to the ‘very high’ RHS-class. The calculation of the WUA – normalized by the spawning area – gives a value of 0.13 for both reproduction periods leading to the final conclusion that the habitat supply is equally affected during both reproduction periods. However, it is noteworthy that for the reproduction period 2010/2011 more areas for spawning are available, consequently the total area of habitat supply is 10 % higher for the reproduction period 2010/2011.

In the context of hypothesis 3 it can be stated that the hypothesis is fulfilled regarding the successful simulation of habitat dynamics in form of time-dependent habitat suitability indices for the whole reproduction period with a subsequent aggregation to RHS-values. In particular, the representation of physical habitats in form of spatial distributions at certain time-steps, time-series of certain locations, and the normalized area of equal HSI-values over the entire reproduction period provides highly valuable information about habitat dynamics as the effects of spatially and temporally varying input variables are included in all modelling steps. Consequently a direct identification of occurring bottlenecks during the reproduction of brown trout is feasible and can be referred back to responsible habitat variables. Moreover, the applicability of the modelling framework to simulate habitat dynamics is underlined by the comparison of two artificial flooding events that differ in their timing to the beginning of the reproduction period and consequently are characterised by different abiotic conditions.

D.2.7 Ecological significance of the modelling framework

To use the habitat modelling framework to simulate the reproduction habitat quality for supporting ecological assessments, the significance of the results from the modelling framework has to be verified from an ecological perspective. Therefore the modelling framework and its result are contrasted to the fluvial ecological processes specified in Chapter A.2.2.

As the quality of the results of the multi-step modelling framework are largely based on the quality of the physical-biota relationships in form of fuzzy-sets and fuzzy-rules, the first evaluation regarding ecological significance is the assurance of proper definitions of the habitat requirements of brown trout during the reproduction period. In this thesis, all fuzzy-sets and fuzzy-rules are developed based on a detailed literature research (Chapter A.2.2.5) and in close collaboration with the biologist Johannes Ortlepp (HYDRA network), who worked over ten years within the River Spoel investigating the self-producing brown trout population. Thus, it can be stated that the best available expert-knowledge combined with literature values are used in defining the habitat demands.

In Chapter A.2.2.1 the importance of habitats in assessing the ecological status of rivers is emphasized (Fig.A.2.6). Per definition the habitat includes both abiotic and biotic attributes as well as their dynamic and static characteristics (Beyer et al., 2010). This leads to a minor restriction as the proposed modelling framework is focused purely on abiotic variables to describe habitat conditions neglecting biotic interactions like competition, predation and dominance (Helfman et al., 2009). However, the response of the modelling framework in form of IHS-, HSI- and RHS-values can be regarded as a biotic component as the cumulative effects of abiotic variables are linked to the habitat requirements of the indicator species brown trout. In addition, the modelling framework allows firstly for the simulation of habitat dynamics as all input variables are considered in their spatial and temporal variability which is a precondition in terms of creation, destruction and maintenance of habitat templates (Poff & Ward, 1990). However, to be precise, the abiotic components include also nutrients and chemical components which are not part of the modelling framework. For the River Spoel the chemical water quality is not a limiting factor and plenty of food resources (mainly benthic macroinvertebrates) lead to high condition factors of brown trout (Ortlepp & Muerle, 2003).

Another ecological aspect includes the system of ecological functions and services (Chapter A.2.2.2, DeGroot, 2000), whereby the focus is set on the ecological functions of the categories ‘regulation’ and ‘habitat’ as they are specified in Tab.A.2.3. One ecological function formulated within the category ‘regulation’, concerns the proper representation of quality and quantity of water and sediments. This is achieved by the application of the 3-dimensional numerical model SSIIM2 which allows a detailed simulation of the hydromorphological variability in a high spatial and temporal resolution. The quality of water and sediments in terms of chemical pollution or transport of contaminants is not considered. Similarly the ecological functions including the nutrient and biogeochemical cycles as well as the genetic diversity are not considered. But a rough approximation of the biogeochemical processes is included by the habitat variable respiration to evaluate the sedimentological, biological and chemical oxygen demand in the river bed. As the modelling framework is based on a habitat-centred view, the ecological functions included in the category ‘habitat’ are of major importance in order to evaluate the habitat modelling framework ecologically. The relevance and significance of simulating reproduction habitats is clarified as reproduction habitats are explicitly mentioned to be an important ecological function. Moreover, the physical and chemical environment of habitats is addressed in Tab.A.2.3 which is approximated in the modelling framework by the habitat variables that are specified for each life-stage during the reproduction period. In total, fourteen habitat variables are included in the modelling framework to describe the habitats of five life-stages during the reproduction period of brown trout, primarily to account for the temporal and spatial variability of the physical environment in the River Spoel. The second ecological function concerns the habitat diversity which is only considered in terms of habitats for the life-stages during reproduction of brown trout that are covered by the spatial and temporal distribution of HSI-values. The last ecological function considers the biological conservation which is not directly addressed within the modelling framework but certainly can be formulated as a future goal because the reproduction is one fundamental process for the development of stable populations which are required to maintain or to improve the biological conservation.

Regarding the ecological scales (Chapter A.2.2.3), the interdisciplinary framework including multi-scale relationships between hydrology, geomorphology, habitat and ecology (Thoms & Parsons, 2002) is used to incorporate the habitat modelling framework. Based on Fig.A.2.7 the modelling framework is primarily assignable to the microhabitat scale as the category of 'hydrological variability' contains mainly hydrodynamics while the category 'morphological adaption' is predominantly based on micro-scaled bed forms. Based on this assignment the response of biota should be focused on individuals. This corresponds fairly well to the investigation at the study site in the River Spoel. From a hydromorphological point of view, this includes the effects of artificial flooding as well as the effects of low flow periods on sediment characteristics that are the main focus of this study. In addition, the brown trout is considered as an indicator species in terms of available reproduction habitat which is also in agreement with the recommended application of biotic response. Therefore it can be concluded that the modelling framework is adequately incorporated in the hierarchical organisation of multi-scale relationships between hydrology, geomorphology, habitat and ecology from Thoms & Parsons (2002).

The last ecological aspect concerns the significance regarding the functionality of the modelling framework as an ecological indicator (Chapter A.2.5) which presupposes that the complexity of fluvial ecosystems are captured by physical, chemical and biological characteristics to allow an evaluation of the ecological quality based on relationships between stressors and indicators. Therefore the modelling framework is faced to the four main indication criteria which are formulated by Jackson et al. (2002). The first criterion includes the conceptual relevance which is fully given by the modelling framework as the results are highly sensitive to stressors (abiotic habitat variables) and respond to these stressors in a certain manner (habitat dynamics). The second criterion concerns practicable aspects (costs, logistics and efforts) which are principally realizable for the modelling framework. However, considering the extensive monitoring and the effort to calibrate and validate the applied modelling steps it can be stated that the total effort to obtain results of the modelling framework is quite high but also indispensable to achieve high quality results. The third criterion is concerned with the response variability which is also provided by the modelling framework as all modelling steps are comprehensible, primarily based on an evaluation of fuzzy-sets and fuzzy-rules that allow a clear assignment of the obtained results to stressors. A minor restriction is made as from an ecological point of view as the obtained IHS-, HSI or RHS-values do not stand alone for a representative ecological assessment. Therefore, a comparison to IHS-, HSI- or RHS-values obtained from a pristine reference site is indispensable. The last aspects include the interpretability and utility which can also be confirmed by the modelling framework as the verbal expressions for fuzzy-modelling as well as the presentation of results in form of spatial distributions, time-series and integrated values allow for an easy communication to scientist, managers and policy makers. According to the classification of indicator species (Young & Sanzone, 2002) the reproduction period of brown trout can be assigned to the group of umbrella and link species as the habitat requirements during reproduction are overlapping with the requirements of other aquatic species (umbrella species). The assignment to the link species arise from the high vulnerability of reproduction processes of brown trout to any changes in the hydromorphological and hyporheic environment which subsequently allows for the investigation of single or multiple stressors (link species).

Based on this analysis it is concluded that the habitat modelling framework and its results have a high ecological significance. In particular, the selection of physical attributes to describe the habitat conditions, their dynamic consideration and comprehensibility emphasizes the capability of the modelling framework to support ecological assessments. However, restrictions are made predominantly regarding the consideration of biotic attributes, chemical processes, nutrients and the required comparison to a reference site. Thus it can be stated that the presence of suitable physical reproduction habitats is certainly a substantial precondition for a stable population of brown trout in the River Spoel but care must be taken to relate these habitat qualities to the functionality of whole fluvial ecosystems.

D.2.8 Summary and conclusions: Case study River Spoel

This chapter aims to summarize the results gained from the application of the habitat modelling framework of the case study at the River Spoel as well as to draw final conclusions regarding the applicability of the multivariate habitat modelling framework. Therefore the monitoring concepts, the numerical modelling with SSIIM2, the simulation of interstitial habitat suitability, the physical habitat modelling with CASiMiR and the aggregation to the final reproduction habitat suitability are addressed.

Abiotic and biotic monitoring

The extensive monitoring program of the study site in the River Spoel (Chapter D.2.2) is primarily focused on the hydromorphological and hyporheic variability to obtain input and verification data for the developed modelling framework. Despite the difficult accessibility to the study site – especially during winter – numerous abiotic data including hydraulic and sediment characteristics, topography, groundwater levels, turbidity, temperature and dissolved oxygen are collected. In terms of biotic monitoring, data including mapping results of spawning areas and survival rates of hatched individuals are available. The monitoring period encompasses two reproduction periods of brown trout and started in September of 2009 and ended in May 2011. The general trends of hydromorphological and hyporheic variability during this investigation period are satisfyingly recorded emphasizing the appropriateness of the applied sampling techniques.

Regarding the hydromorphological variability the analysis of the sediment samples is used to determine the effects of artificial flooding on the gravel river bed of the River Spoel as well as to determine the sediment infiltration masses during the regulated flow period encompassing the reproduction period of brown trout. The effects on sediment characteristics of the river bed due to artificial flooding differ between 2009 and 2010. In 2009 fine sediments are successfully flushed out of the interstices of the gravel bed, while in 2010 several samples show increased amounts of fine sediments, although the increase does not reach critical limits in terms of reproduction. The sediment infiltration rates are similar in both investigation periods. A comparison with published data of infiltration masses indicates low infiltration rates in the River Spoel which is reliable as the study site is directly located downstream of the dam and fine sediments are delivered mainly during precipitation events and snow melt.

The hyporheic variability is recorded using continuous measurements of the temperature, regular measurements of the interstitial dissolved oxygen and one collection of groundwater levels to derive the direction of the vertical hydraulic gradient during regulated flow conditions. The seasonal variations of temperature and oxygen contents are captured successfully. A comparison of the groundwater levels to the surface water levels allow for the identification of up- and downwelling zones in the study site. Two upwelling areas are identified in the study site, they are located at the end of the two riffles downstream of SP1 and upstream of SP3.

In addition to the characteristic that the spatial and temporal resolution of the sampling can never be high enough, several improvements of the abiotic monitoring concept are recommended to reduce the number of required assumptions and to increase the reliability of the simulated data. This includes mainly the lacking data of suspended load measurements during artificial flooding and flow regulation as the sediment-fluxes are an important input parameter for the numerical model SSIIM2. Additionally the lacking measurements of permeability to verify the calculated values using the Kozeny-Carman-Equation would increase the reliability of the obtained results. Another aspect to be mentioned concerns the missing sediment samples in-between the reproduction periods to verify the temporal progress of sediment infiltration processes.

Regarding the biotic monitoring a high variability of survival rates is obtained within each spawning area and in each single artificial redd. This variability makes it difficult to use the sampled data for verification purposes of the simulated incubation habitat quality by the habitat model CASiMiR. The applied method (egg capsules) was not tested before and the observed variations of survival rates could not be purely assigned to varying abiotic conditions as other factors like diseases, fungal infection or the poor weather conditions during installation can also be a reason for the obtained variations. The attempt to determine survival rates for emerging larvae totally failed. Consequently no verifications of the simulated emergence habitat and the final success of reproduction are feasible.

Despite these uncertainties and shortcomings during monitoring all modelling steps of the modelling framework are successfully performed and the results are verified, where feasible, on the available data which is focused on in the following section.

Simulation of hydromorphological variability

The 3D-sediment-transport model SSIIM2 is used to simulate the hydromorphological variability in the River Spoel to reproduce the measured effects of artificial flooding and the sediment infiltration processes during the reproduction period. Given the availability of measured data for two artificial floods and two reproduction periods, a calibration and validation of the model is realizable. Therefore SSIIM2 is calibrated based on the collected data in 2009/2010 and subsequently validated on the available data in 2010/2011.

For the simulation of artificial flooding (Chapter D.2.3.2) the hydraulic calibration is performed based on a comparison of measured and simulated water levels and a corresponding adaptation of the roughness. The morphological calibration uses the critical Shields number (θ=0.065) and the exponent (m=0.3) of the hiding/exposure function of Wu et al. (2000) to adapt the simulated bed level changes and particle size distribution to the measured values. The simulated bed level changes are in the same order of magnitude indicating that the river bed is in motion and a resorting of particle size distribution is invoked by artificial flooding. However, for both artificial floods the measured bed deformations cannot fully be reproduced by SSIIM2. These discrepancies may also result from the insufficient spatial resolution of sediment samples that were taken only in spawning areas and do not reflect the whole sediment diversity in the river reach. Comparing the depth of invoked bed alterations (± 5 cm) and subsequent loosening of sediments to typical redd depths yields that the alterations are close to an absolute minimum to allow for a successfully digging of redds. Regarding the particle size distributions, SSIIM2 successfully reproduced the effects of artificial flooding as for all available sediment samples the measured fractional changes of particle sizes are well reflected by the numerical model. Although minor restrictions are made regarding the simulation of bed deformations it is concluded that SSIIM2 is able to simulate the effects of artificial flooding on sediment characteristics in the River Spoel. Particularly the effects on particle size distributions after flooding are adequately reproduced emphasising the functionality of the numerical model SSIIM2.

The simulation of sediment infiltration processes in SSIIM2 (Chapter D.2.3.3) is primarily approximated by the depositions of fine material in the surface layer of the river bed. For calibration the measured infiltration masses at the end of the reproduction period are compared to the simulated infiltration masses. Thereby the key calibration factor is the exponent of the hiding/exposure function (m=0.7) of Wu et al. (2000) which is used to adjust the equilibrium between deposition and resuspension. However, given the lacking sediment data to verify the temporal progress of sediment infiltration processes, it is assumed that the semi-empirical approach of Schaelchli (1993) gives at least an approximation of the temporal progress. Consequently, the simulation results obtained by the semi-empirical approach are used for calibrating the temporal progress of sediment infiltration simulated by SSIIM2. In preliminary simulation runs it is found that an equilibrium between incoming suspension loads and resuspended material is achieved resulting in no further depositions. This implies that additional calibration factors are required to avoid the state of equilibrium in the considered investigation period. Therefore the settling velocity is chosen as an additional calibration factor to adjust the equilibrium state, whereby a reduction factor of 10 (for fine sediments) was found to produce reliable results. Applying this calibration strategy SSIIM2 is able to reproduce both the magnitude of infiltration masses (7 kg/m²-16 kg/m²) as well as the temporal progress of sediment infiltration. But a comparison between SSIIM2 and the semi-empirical approach regarding the spatial pattern of infiltration masses indicates large discrepancies outside of the spawning areas which are explained by the strong influence of the variables d_{10}/d_m and the vertical hydraulic gradient in the semi-empirical equations of Schaelchli's approach.

Based on these outcomes it is concluded that SSIIM2 is able to reproduce the sediment infiltration processes in the River Spoel with restrictions regarding the simplification of the sediment infiltration process in order for the model to function and the strong dependency on the applied calibration factors that can be adjusted to produce a wide range of different infiltration masses.

Simulation of hyporheic variability

The hyporheic variability in the River Spoel (Chapter D.2.4) is approximated by an indicator expressed by the interstitial habitat suitability (IHS) combining the variability of the input parameters permeability, temperature and hyporheic respiration via fuzzy-modelling. For the River Spoel, the habitat requirements are orientated on the reproduction of brown trout which is subdivided into the life-stages during incubation (eyed-egg, hatching and larval stage) as the habitat demands on interstitial habitats differ among the life-stages. The fuzzy-simulation is performed within each element of the computational grid for each time-step to assure the representation of spatial and temporal variability of the input variables. While the permeability functions as an indicator for the sediment characteristics and defines the capability of the river bed to transport oxygenated water and metabolic waste products, the interstitial temperature reflects the metabolic activity and defines upper and lower lethal limits. Lastly the hyporheic respiration indicates the summarized oxygen demand of biogeochemical processes.

The obtained IHS-values in the River Spoel reflect the different habitat demands during the incubation period that are lowest during the eyed-egg stage, highest during the hatching stage and in-between for the larval stage. Further, the effects of hyporheic variability are indicated by considerable fluctuations visualized in the time-series of IHS-values. Analysing the outcomes of the fuzzy-modelling indicates that these fluctuations are predominantly invoked by the variations of the interstitial temperature close to the critical range of tolerated temperatures. This is evidently visible for the hatching stage, as limiting temperatures meet the highest requirements on the interstitial habitats leading to fluctuations between ‘high’ and ‘medium’ IHS-values. Regarding the effect of permeability, it is observed that the permeability mainly determines the magnitude of IHS-values but also lead to continuously decreasing IHS-values. This is mainly indicated during the larval stage, where the interstitial temperatures are not in a limiting range. The influence of hyporheic respiration is found to be mostly not limiting the IHS-values within the spawning areas as critical respiration values are only reached in areas where high sediment infiltration with consequently low permeability are observed. However, this is also the most uncertain input variable as it is based on measurements performed in 2005 in combination with the measurements of the dissolved oxygen values in the investigation periods as well as on a rough estimation of available particle surfaces that allow microbial growth. Restrictions for the fuzzy-model to simulate IHS-values are made regarding the exchange processes between groundwater and surface water that are not explicitly represented within the approach. This interaction certainly have an effect on the biogeochemical processes and consequently on the quality of interstitial habitats. In order to investigate the functionality of IHS-values as an indicator of hyporheic variability, the obtained results are contrasted to corresponding indication criteria, yielding a high indication value with minor restriction regarding practical aspects. Furthermore, comparison data of a pristine reference site would be beneficial to allow for well-founded ecological assessments.

To conclude the findings of the multivariate fuzzy-model for interstitial habitats for the River Spoel, it is determined that the simulated IHS-values provide highly valuable information about the hyporheic variability. In particular, the dynamics of IHS-values allow for a spatial and temporal assessment of interstitial habitat qualities in terms of hydromorphological and hyporheic variability. But restrictions are made regarding an adequate representation of hyporheic exchange processes and a comparison to a pristine reference site would increase the resilience of the obtained results for supporting the evaluation regarding the ecological functionality of interstitial habitat conditions.

Simulation of physical habitats during reproduction

To simulate the habitat conditions during the reproduction of brown trout with CASiMiR the life stages spawning, incubation, and emergence are considered whereby the incubation period is further subdivided into the eyed-egg-stage, hatching stage and larval stage (Chapter D.2.5).

For the spawning stage (Chapter D.2.5.1) a two-stage fuzzy-approach is applied considering in a first step the sediment spawning index SSI, which evaluates the suitability of the sediment characteristics for spawning based on a classified particle size composition using sand, gravel, pebbles and cobbles. In a second step the SSI is linked to the hydraulic variables water depth and flow velocity resulting in the habitat suitability index for spawning (HSI_{spawn}). In contrast to common habitat modelling approaches for spawning habitats the two-stages of the fuzzy-approach allows for a more precise formulation of habitat requirements whereby the intermediate result (SSI) provides on its own highly valuable information regarding the sediment characteristics for spawning. Particularly the dynamic simulation of classified particle size distributions allows considering requirements on the amount of fine sediments or the maximum movable particle size during redd digging which cannot be considered using single or static sediment indices. Based on the analysis of the spawning habitat quality in the River Spoel it is found that in both spawning periods (2009, 2010) about 45% of the study site is characterised by areas where spawning is feasible ($HSI_{spawn} > 0$). However, considering only the ‘high’ and ‘very high’ HSI-classes, these areas are reduced in 2009 to 19 % and in 2010 to 23 %. Although this difference is marginal, it is confirmed by the total number of counted in both spawning seasons redds (2009: 43 redd, 2010: 48 redds). In order to investigate the effects of artificial flooding in the River Spoel, the two investigated periods (2009, 2010) with different timing of artificial flooding before the spawning season, are compared and it is found that the longer period in 2010 between artificial flooding and spawning season has no negative effects on the spawning habitat quality. Facing the spatial distribution of the simulated values of HSI_{spawn} to the distribution of mapped spawning redds result in a high performance for both spawning seasons as almost all mapped redds are located in areas with a ‘high’ or ‘very high’ habitat suitability indices. The verification of the simulated HSI_{spawn} on two different abiotic conditions (2009, 2010) using the same predefined fuzzy-sets and fuzzy-rules assures the functionality of CASiMiR to simulate the selection of spawning sites for brown trout.

The habitat simulations for the incubation period (Chapter D.2.5.2) are also based on a two-stage fuzzy-approach using the previously mentioned interstitial habitat suitability (IHS) as a first step which is linked to the habitat variables bed level change and the direction of the vertical hydraulic gradient in a second step. However, the obtained results of CASiMiR (HSI_{egg}, HSI_{hatch}, HSI_{larv}) are only considered within the spawning areas as only in areas where spawning is possible, an investigation of the incubational habitat is relevant. The variable bed level change accounts for the risk of eggs and larvae to be flushed out of the protecting interstitials in the river bed while the direction of the vertical hydraulic gradient is used to indicate up- and downwelling areas, whereby only upwelling areas are limiting the incubation habitat as groundwater entering the interstitials prevents the oxygen supply of eggs and larvae due to the low oxygen content of groundwater. Another aspect considered in the simulation of the quality of the incubation habitat is that limited habitat conditions within one life-stage cannot be compensated by better habitat conditions during the following time-step. In the River Spoel it was found that the habitat variables of the second fuzzy-step are of minor relevance as no erosion occurs during the regulated flow period and the upwelling areas are outside of the spawning areas. This implies that the habitat quality during incubation is predominantly controlled by the interstitial habitat suitability. According to the areas of equal HSI, the eyed-egg stage is largely characterised by ‘very high’ HSI-values, which are slightly reduced from approximately 90 % to 86% during the incubation period 2009/2010 while for 2010/2011 the reduction is 8 %. The habitat availability is most strongly affected during the hatching stage providing ‘high’ values of HSI_{hatch} at the beginning and ‘medium’ values of HSI_{hatch} at the end of the hatching stage. For the larval stage a ‘high’ value of HSI_{larv} is dominating in the River Spoel. In all life stages the suitable HSI-values are continuously reduced reflecting the impact of critical interstitial temperatures and the decreasing permeability due to sediment infiltration processes. Contrasting both reproduction periods indicates larger areas to be not suitable in 2010/2011 than in 2009/2010. A comparison with the mean observed survival rates in the spawning areas SP1-SP3 offered a very weak relation to the most critical HSI-values obtained during hatching. However, the obtained survival rates in the field cannot purely be traced back to varying abiotic conditions as multiple factors such as diseases, fungal infections, and egg handling may be responsible for the high observed variance of survival rates which occurred not only in spawning areas but also in each artificial redd. Thus, the comparison does not necessarily reflect the model performance.

The habitat simulation for the emergence habitat (Chapter D.2.5.3) is the last life-stage to be considered in the modelling framework. The simulation of HSI_{emerg} is based on a fuzzy-model that links the variables bed level change, geometric mean diameter and the percentage quantities of particle sizes < 8 mm. While the bed level change predominantly accounts for physical damages due to particles in motion and displacement, the geometric mean is used as an indicator for the available pore size which is additionally considered by the amount of particle sizes < 8 mm. In the River Spoel it is indicated that none of the applied habitat variables are in critical ranges, this leads to 'very high' values for HSI_{emerg} in all spawning areas and in both reproduction periods. Hence, the emergence period is not limiting the reproduction success in the River Spoel. However, the selection of habitat variables to describe the sediment characteristics for emergence is relatively poor. From a morphological perspective much better descriptors are available. For example, the porosity which is also a direct output of the numerical model SSIIM2 much better reflects the available pore sizes for emergence. However, as the selection of habitat variables depends also on the availability of biological data to determine the habitat requirements, the porosity could not be used as a habitat variable as no investigations are available relating porosity to the successful emergence of larvae.

To conclude the simulations of physical habitats it can be established that the representation of physical habitats in form of spatial distributions at certain time-steps, time-series of certain locations, and the normalized area of equal HSI-values over the entire reproduction period provides highly valuable information about habitat dynamics as the effects of spatially and temporally varying input variables are included in all modelling steps. Consequently, a direct identification of occurring bottlenecks during the reproduction of brown trout is feasible and can be referred back to responsible habitat variables. In the River Spoel it is found that the spawning and emergence stages are not limiting the reproduction success and the most restricting conditions occurred during hatching, predominantly caused by critical interstitial temperature and permeability conditions.

Simulation of Reproduction Habitat Suitability (RHS)

The last step of the modelling framework includes the aggregation of the simulated HSI-values to an integrated result (Chapter D.2.6) that allows for an easy identification of critical habitat conditions for available reproduction habitats of brown trout. The HSI-values of each life-stage are aggregated by a multiplicative linkage of the minimum HSI-values in each life-stage to the reproduction habitat suitability (RHS). The application of the minimum HSI-values is reasonable as the most critical habitat conditions have to be considered for the evaluation of the entire reproduction habitat. The multiplicative linkage is based on the assumption that a 'low' HSI-value in a certain life-stage cannot be compensated by a 'high' HSI-value in another life-stage. For example if the incubation habitat quality is 'low' the RHS-value cannot get a higher suitability than 'low' due to a 'very high' emergence habitat. For these reasons it is assumed that the multiplicative linkage of minimum HSI-values in the life-stages during reproduction is an appropriate method to get a summarized result of the entire modelling framework.In the River Spoel the RHS values varies between 0 and 0.25. However, it is important to note that a RHS-value of 0.25 corresponds to an average of 'high' HSI-values in each life-stage of the reproduction period. Analyzing the obtained RHS-values in the spawning areas indicated that for both reproduction periods approximately 50 % are not suitable for reproduction or have a 'low' RHS-value, while the other 50 % have RHS-values in the range of 'medium' to 'very high'. In 2009/2010 more areas are assigned to the 'medium' class while in 2010/2011 more areas are assigned to the 'very high' RHS-class. The calculation of the WUA – normalized by the spawning area – gives a value of 0.13 for both reproduction periods leading to the final conclusion that the habitat supply is equally affected during both reproduction periods. However, it is noteworthy that for the reproduction period 2010/2011 more areas for spawning are available, which leads to a higher reproductive habitat supply (10 %) in 2010/2011.

Finally, it can be stated – based on these outcomes – that the earlier artificial flooding in 2010, which provides more time for sediment infiltration process affecting the sediment characteristics, has no negative impact on the supply of reproduction habitat.

Ecological significance of the multivariate fuzzy-logical modelling framework

The ecological significance of the modelling framework is evaluated based on the ecological processes formulated in Chapter A.2.2 including the definition of habitats, ecological functions, ecological scales and ecological indicators. Regarding the definition of habitats (Chapter A.2.2.1) the modelling framework is well suited to represent the abiotic attributes of a habitat. However, there are restrictions that must be considered mainly regarding the lack of the biotic interactions including competition, predators and dominance. Although not that relevant in the River Spoel, the water quality in terms of chemical conditions or the availability of nutrients are neglected in the modelling framework. However, the results of the modelling framework in the form of IHS-, HSI- and RHS-values are a biotic response as the cumulative effects of abiotic variables are linked to the habitat requirements of the indicator species brown trout. Moreover the modelling framework allows firstly for the simulation of habitat dynamics as all input variables are considered in their spatial and temporal variability which is a precondition in terms of creation, destruction and maintenance of habitat templates. Further, the modelling framework encompasses major ecological functions (Chapter A.2.2.2) like the regulating ‘quantities and qualities of water and sediments’. The ecological function ‘habitat diversity’ is provided by the spatial distribution of the obtained habitats for different life-stages and although, the ‘biological conservation’ is not directly addressed by the modelling framework, the simulation of reproduction habitats represents one fundamental process for the development of stable population which is required to maintain or to improve the biological conservation. Regarding the scales of ecology (Chapter A.2.2.3) the modelling framework is adequately incorporated into the hierarchical organisation of multi-scale relationships between hydrology, geomorphology, habitat and ecology. For the last aspect, the ecological indication value (Chapter A.2.2.4), it can be stated that the modelling framework is well suited to support ecological assessments as the conceptual relevance is fully given by the modelling framework because the results are highly sensitive to stressors and all modelling steps are comprehensible allowing a clear assignment of the variability of results to certain stressors. Further, the presentation of results in form of spatial distribution, time-series and integrated values allow a detailed interpretation and the verbal formulation included in fuzzy-modelling enable an easy communication to scientist, managers and policy-makers. A minor restriction is made regarding the practical aspects as the efforts for the extensive monitoring, the calibration and validation of numerical and habitat modelling is time- and labour intensive but indispensable to achieve high quality results. Finally, the application of the early life-stages of brown trout as an indicator species can be assigned to the categories umbrella and link indicators, as the brown trout has overlapping habitat requirements with other aquatic species but also responds highly sensitive to any changes of the hydromorphological and hyporheic environment allowing to investigate single or multiple stressors. Therefore, it is finally concluded that the presence of suitable physical reproduction habitats (obtained by the modelling framework) is of high ecological significance and is well suited in supporting ecological assessments. However, although the availability of suitable reproduction habitats is certainly a substantial precondition for the settlement of indicator species, care must be taken to relate these habitat qualities to the functionality of whole fluvial ecosystems.

PART E: CONCLUSIONS

E.1 Summary of the work

The complexity and dynamic nature of ecosystem processes impose high requirements on the approaches, methods and modelling techniques applied to support ecological assessments of rivers. Particularly the interactions of abiotic and biotic variables, the high spatial and temporal variability of parameters and processes and the interdisciplinary research field present a special challenge on the development of appropriate tools. Given the naturally dynamic creation, destruction and maintenance of habitat templates in rivers (habitat dynamics) the habitat can be regarded as a basic element of fluvial ecosystems. Accordingly, high demands are placed on aquatic habitat modelling techniques emphasizing the need for the improvement and further development of existing approaches.

The present study predominantly addresses three research fields encompassing the hydromorphology, the fluvial ecology and the hyporheic interstitial of rivers. All disciplines are involved by interacting processes defining the quality of reproduction habitats for gravel-spawning fish. Consequently, the proposed multi-step habitat modelling framework can be primarily considered as an advancement of physical fish habitat modelling. In this work, the advancements of existing habitat modelling approaches are focused on implementing the hydromorphological and hyporheic variability in physical habitat modelling considering all variables that describe the habitat in their spatial and temporal variability to allow a dynamic representation of habitat suitability. Therefore a sophisticated 3D-numerical model to simulate the sediment dynamics in combination with additional habitat variables is applied to obtain detailed information about the abiotic habitat characteristics during the reproduction period which provide the basis for proper habitat modelling. The reproduction period of gravel-spawning fish works as an excellent indicator for habitat dynamics, as the life-stages during reproduction (spawning, incubation, and emergence) are not only characterised by high requirements but also by different requirements on the habitat. The proposed multi-step habitat modelling framework addresses each life-stage during the reproduction by an appropriate selection of key habitat variables that are linked via a multivariate fuzzy-logic model to simulate habitat suitability indices reflecting the biotic response to varying abiotic conditions. The obtained results are presented as spatial distribution maps and time-series of habitat suitability indices as well as a study-wide integrated value expressed by the areas of equal habitat suitability classes. The last step of the modelling framework includes the aggregation of the dynamic habitat values to a temporally integrated parameter and the final result of the modelling framework, the reproduction habitat suitability.

The introduction of this thesis formulates three hypotheses that are approached, tested, discussed and answered in the presented work. Following the background and basic information presented in part A, the necessity of simulating habitat dynamics and a concretization of the hypotheses is addressed in part B. The concept of the modelling framework is explained in part C, while part D contains the application of the modelling framework and all relevant evaluations and assessments. The following sections verify the initially drawn hypothesis:

Hypothesis 1: hydromorphological variability

The first hypothesis includes that the most relevant fluvial dynamic processes influencing the sediment characteristics for reproduction of gravel-spawning fish species can be simulated using a 3D-sediment-transport model. In order to test the capabilities of the numerical model SSIIM2, the model is applied for the simulation of artificial floods to investigate the hydromorphological effects of bed level changes and sorting processes on sediment characteristics. Regarding this aspect, hypothesis 1 is confirmed as SSIIM2 adequately reproduced the particle size distribution after artificial flooding and only minor restrictions are made in terms of the spatial distribution of bed level changes. Although similar patterns of erosion and deposition zones are indicated, discrepancies occur only on a small scale. However the simulated bed level changes are in the same order of magnitude indicating that the river bed is in motion and a resorting of particle size distribution is invoked by artificial flooding. Moreover, as the bed level changes are close to the maximal possible accuracy of topographic measuring and the sediment samples were taken only in spawning areas and do not reflect the whole sediment diversity in the river reach, it is concluded that the discrepancies are most likely due to insufficient initial data and not due to limitations of the numerical modelling.

The second aspect of hypothesis 1 includes the process of sediment infiltration during low flow periods and the consequential accumulation of fine sediments in the interstitials of gravel river beds. Regarding the sediment infiltration, experimental investigations of sediment infiltration processes in a laboratory flume (Schaelchli, 1993) were successfully reproduced with SSIIM2 using hiding/exposure functions to account for the infiltration resistance of the gravel river bed and of progressive occlusion of available pore sizes due to infiltrating fine particles. But severe assumptions and simplifications are required to reproduce the infiltration processes numerically. On the one hand the infiltration in SSIIM2 is approximated by the deposition of particles in the active layer, which differs from physical experiments that have shown a deposition between the surface and subsurface layer with an unhindered transport of infiltrating material through the coarse surface layer. On the other hand, the calibration factors in the hiding/exposure functions are spatially and temporally constant which is in contrast to the dynamically varying infiltration resistances. In the case study for the River Spoel sediment samples were only available at the beginning and end of each reproduction period and for calibration of the temporal progress of sediment infiltration processes in-between the numerically simulated infiltration masses are compared to the results obtained by the semi-empirical approach of Schaelchli (1993). The semi-empirical approach thereby is assumed to provide a rough estimation of the temporal progress of infiltration processes. Based on these assumptions and the aforementioned calibration strategy the simulation of sediment infiltration processes reproduced the spatial and temporal distribution of measured infiltration masses to a sufficient accuracy. The obtained simulation results are however strongly dependent on the applied calibration factors which can be adjusted to produce a wide range of different infiltration masses.

In context of hypothesis 1, it is finally concluded that a 3D-numerical modelling tool can be applied to reproduce the hydromorphological variability with corresponding effects on sediment characteristics (effects of artificial flooding and sediment infiltration) that are required for the reproduction of gravel-spawning fish. However, significant restrictions are made regarding the exact reproduction of bed deformations invoked by artificial flooding and the required simplifications for sediment infiltration in order for the model to function. Further, special care must be taken with regards to the applied formulas, empirical values and calibration factors affecting the numerical results.

Hypothesis 2: hyporheic variability

The second hypothesis includes the representation of the hyporheic variability by linking key habitat factors describing the interstitial habitat suitability for reproduction of gravel-spawning fish species via a multivariate fuzzy-logic approach. Therefore the permeability is used to describe the capability of sediment characteristics to transport oxygen-rich surface water and metabolic waste products. The interstitial temperatures are applied to indicate the metabolic activity and defining upper and lower lethal and sub lethal limits, while the hyporheic respiration is used as a key factor to describe the oxygen demand of biogeochemical processes. Linking these key factors to spatially and temporally varying values of interstitial habitat suitability for different life-stages during the incubation period of gravel-spawning fish (eyed-egg, hatching, larvae) produced reliable results. Particularly the impact of short-term effects on habitat quality like critical temperatures and the impact due to long-term effects like a continuously decreasing permeability could dynamically be determined. Furthermore the applicability as an indicator of hyporheic variability is verified on basic requirements on interstitial habitat and general criteria for indicators. In particular, the conceptual relevance, interpretability, and response variability yield a high indication value for the method to simulate interstitial habitat suitability. However, restrictions are made regarding an appropriate representation of the exchange processes between groundwater and surface water (up- and downwelling processes). These exchange processes can have a detrimental influence on interstitial habitat conditions. In addition data from a pristine reference site would be required to allow for proper ecological assessments.

Based on these results, it is concluded that hypothesis 2 is generally supported, as impacts of spatially and temporally varying interstitial parameters are well reflected by the interstitial habitat suitability values. This allows for a detailed identification of bottlenecks regarding the interstitial habitat quality during the reproduction habitat. However, improvements regarding the implementation of a proper description of hyporheic exchange processes would be beneficial for this fuzzy-approach. In addition a well-founded verification would increase the resilience of the obtained modelling results.

Hypothesis 3: physical habitat modelling and aggregation

The last hypothesis of this thesis concerns the multi-step habitat modelling framework to simulate the habitat dynamics of all life-stages during the reproduction period of gravel-spawning fish with a subsequent aggregation to a single parameter: the reproduction habitat suitability. The reproduction is subdivided into the life-stages spawning, incubation and emergence, while the incubation habitat is further subdivided into the eyed-egg, hatching and larval stage. For each life-stage the spatial and temporal variations of key habitat variables and habitat requirements are identified and linked by multivariate fuzzy-modelling to habitat suitability indices. For the spawning habitat totally six habitat variables are applied. While the fractions sand, gravel, pebbles and cobbles are used to describe the sediment characteristics, the hydraulic characteristics are represented by the variables water depth and flow velocity. Regarding the incubation habitat the interstitial habitat suitability (hypothesis 2) is combined with the bed level changes and the direction of the vertical hydraulic gradient to consider the possible erodibility of buried eggs and larvae as well as the identification of upwelling processes that prevent the oxygen supply to eggs and larvae. The emergence habitat is described by the geometric mean particle diameter, the amounts of particles less than 8 mm and the bed level change to describe the available pores for emergence and the risk of displacements and physical damage. Finally, the obtained time-dependant habitat suitability indices are aggregated by a multiplicative approach to the reproduction habitat suitability that incorporates all previously simulated results.

The simulated habitat suitability indices in the River Spoel allow for a representation of physical habitats in the form of spatial distribution maps for different time-steps, time-series for different locations and an integrated habitat supply over the entire reproduction period. This provides highly valuable information about habitat dynamics as all spatially and temporally varying input variables are considered in the multi-step habitat modelling framework. Consequently a direct identification of occurring bottlenecks during the reproduction of brown trout is feasible and can be referred back to responsible habitat variables. In the River Spoel it is found that the spawning and emergence stages are not limiting the reproduction success and the most restricting conditions occurred during hatching. The limitations were predominantly caused by critical temperature and permeability conditions. The aggregated reproduction habitat suitability contains the summarized effects of all varying abiotic conditions during the reproduction period of gravel-spawning fish and allows for a quick identification of the availability and quality of reproductive habitats.

However, regarding the quality and verification of the obtained results restrictions have to be formulated. While the spawning habitat could be adequately verified, a comparison of the survival rates of hatched individuals to the corresponding habitat suitability shows only a very weak relation. Given the very high variance of survival rates in each artificial redd and within each egg capsule, the survival rates cannot purely be traced back to varying abiotic conditions as multiple factors such as disease, fungal infections and egg handling may be responsible for the high variance. Regarding the emergence success the selection of habitat variables is poor as much better descriptors for available pores in river beds are available (e.g. porosity or pore space). However, they are not applicable as no biological data is available which describes the habitat requirements of these variables. Furthermore restrictions occur due to the limited consideration of the hyporheic exchange processes with varying vertical hydraulic gradients and a proper representation of biogeochemical processes. This is particularly relevant when considering the characteristic local redd morphologies with the typical redd pot and hump, which favours the infiltration of oxygen-rich surface water. Lastly, restrictions occur as the cleaning processes during redd digging is not considered within the habitat modelling framework which substantially increases the permeability within the redds. As these two latter aspects would significantly increase the quality of reproductive habitats but are neglected within the modelling framework, it is concluded that the simulated reproduction habitat suitability may be underestimated.

Hypothesis 3 is confirmed regarding the successful simulation of HSI-values over the entire reproduction period that provides highly valuable information about habitat dynamics, however restrictions are made regarding the lack of proper verification data for the obtained simulation results and regarding the lack of relevant abiotic processes such as the impact of hyporheic exchange, detailed redd morphologies and the cleaning effect during redd digging.

Since the presented multi-step fuzzy-logical habitat modelling framework was only applied in the study site of the River Spoel the general functionality and transferability to other study sites in same and different eco-regions, to other gravel-spawning fish species or to other boundary conditions (e.g. unregulated flow) is not given within the presented work. For the support in ecological assessments, the application of the modelling framework on pristine river reaches (reference sites) would be beneficial as this allows for a comparison of the current ecological situation to the pristine ecological situation which is indispensable for proper ecological assessments.

Final remark

Although the imposed hypotheses are widely confirmed with several restrictions, it is worth noting that models in general are never able to fully reflect the dynamic behaviour of rivers and its ecological relations. The simplification of the physical and ecological processes requires a well-founded verification of obtained simulation results against field observations and reference sites. The highest benefit of the proposed modelling framework comprises the spatial and temporal consideration of conventional and new habitat variables resulting in a detailed representation of habitat dynamic processes occurring in river reaches. Further, the presented work is the first attempt to simulate the quality of reproduction habitats for gravel-spawning fish using physical habitat modelling. Possible future applications predominantly include the support of ecological impact assessments but also the applicability as an instrument supporting the management and planning processes of restoration measures (e.g. for re-establishing reproducing fish population in rivers) as the simulation of reproduction habitats presents one fundamental process for the development of stable fish populations.

E.2 Future research

Additional efforts should be undertaken to evaluate the multi-step habitat modelling framework regarding the specifications of fuzzy-modelling. A sensitivity analysis investigating aspects such as the variations in single membership functions (e.g. trapezoidal, triangular), the degree of overlapping membership functions, the number of membership functions for each habitat variable as well as the influence of different expert-knowledge (specification of fuzzy-rules from independent fish biologists) would increase the resilience of the results of the modelling framework.

In addition to a further investigation regarding the specifications of fuzzy-models the quality of the results of the modelling framework are predominantly determined by the quality of the input variables. The better the abiotic characteristics of a river reach are reproduced (analytically or numerically) the higher the quality of the obtained results. This leads to future research needs in terms of numerical modelling of sediment-dynamics but also to a more sophisticated consideration of hyporheic interstitial processes. Regarding the numerical modelling of morphodynamic processes further research with a well-founded verification of the use of variable porosities in numerical modelling of sediment transport processes is required. This would also be very beneficial for ecological assessments due to the high indication value of porosity to describe interstitial characteristics. Moreover, the presently implemented concepts in numerical models to simulate sediment exchange processes between different sediment layers (vertical sorting processes) are another aspect of future research. Physical processes like the unhindered settling of infiltrating particles through a coarse surface layer or the transport of fine particles in-between the interstitials of a river (lateral infiltration, bed filtration) are not reproducible in current numerical models.

In terms of the hyporheic interstitial processes another important field of research is addressed. The interactions between surface water, hyporheic zone and groundwater have a substantial effect on interstitial habitat conditions. To allow a detailed description of interstitial habitat the hydrological, sedimentological, chemical and microbial processes have to be identified and quantified. Next to consideration of the multidimensional hydraulic gradients, the biogeochemical processes play a major role not only regarding the oxygen balance but also regarding the stabilisation of gravel-frameworks (biostabilisation).

Another important development can be undertaken in the direction of biological research. The consideration of key variables obtained by highly sophisticated models is only applicable if corresponding information about a biotic response exists. Therefore a close collaboration between modellers and biologists is indispensable for developing key habitat variables which yield a high indication value.

Lastly, advancements in habitat modelling are required to allow interfaces to population models. Hence, in the context of this thesis one important question must be addressed in future research: how much reproduction habitat quality and supply is required by gravel-spawning fish to allow for the development of stable naturally reproducing fish populations?

Bibliography

Ackers, P. & W.R. White (1973): Sediment transport: A new approach and analysis. Journal of Hydraulics Division, ASCE, 99(HY11): 2041–2060.

Acreman, M.C. & M.J. Dunbar (2004): Defining environmental river flow requirements, a review. Hydrology and Earth System Science, 8(5): 861–876.

Adriaenssens, V., De Baets, B., Goethals, P.L.M. & N. De Pauw (2004): Fuzzy rule based models for decision support in ecosystem management. Science of the Total Environment, 319: 1–12.

Adriaenssens, V., Goethals, P.L.M. & N. De Pauw (2006): Fuzzy knowledge–based models for prediction of Asellus and Gammarus in watercourses in Flanders (Belgium). Ecological Modelling, 195: 3–10.

Ahmadi–Nedushan, B., St–Hilaire, A., Bérubé, M., Robichaud, E., Thiémonge, N. & B. Bobée (2006): A review of statistical methods for the evaluation of aquatic habitat suitability for instream flow assessment. River Research and Applications, 22: 503–523.

Ahmadi–Nedushan, B., St–Hilaire, A., Bérubé, M., Ouarda, T.B.M.J. & E. Robichaud (2008): Instream flow determination using a multiple input fuzzy–based rule system, a case study. River Research and Applications, 24: 279–292.

Ahrens, J.P. (2000): A fall–velocity equation. Journal of Waterway, Port, Coastal, and Ocean Engineering, ASCE, 126(2): 99–102.

Alabaster, J.S. & R. Lloyd (1980): Water quality criteria for freshwater fish, Food and Agriculture Organization of the United Nations, Butersworth, London.

Allen, J.D. & M. Castillo (2007): Stream Ecology: Structure and Function of Running Waters. Second Edition, ISBN: 9781402055836.

Allan, A.F. & L. Frostick (1999): Framework dilation, winnowing, and matrix particle size: the behaviour of some sand–gravel mixtures in a laboratory flume. Journal of Sedimentary Research, 69(1): 21–26.

Almeida, G. & J. Rodríguez (2009): Integrating sediment dynamics into physical habitat models. 18th World Imacs/ModSim Congress, Cairns, Australia: 2258–2264.

Alonso, C.V., Theurer, F.D. & D.W. Zachmann (1996): Sediment intrusion and dissolved oxygen transport model SIDO. U.S. Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, Technical Report 5, Oxford, Mississippi.

Armstrong, J.D., Kemp, P.S., Kennedy, G.J.A., Ladle, M. & N.J. Milner (2003): Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fisheries Research, 62: 143–170.

Armstrong, J.D. & K.H. Nislow (2006): Critical habitat during the transition from maternal provisioning for freshwater fishes. Journal of Zoology, 269: 403–413.

Bachman, R.A. (1984): Foraging behaviour of free–ranging wild and hatchery brown trout in a stream. Trans American Fish Society, 113: 1–32.

Bagnold, R.A. (1966): An approach to the sediment transport problem from general physics. Professional Paper 422–J, USGS, Washington D.C., USA.

Bain, M.B. (1995): Habitat at the local scale: multivariate patterns for stream fishes. Bulletin Français de la Pèche et de la Pisciculture, 337/338/339: 165–177.

Baker, D.W., Bledsoe, B.P., Albano, C.M. & N.L. Poff (2010): Downstream Effects of Diversion Dams on Sediment and Hydraulic Conditions of Rocky Mountain Streams. River Research and Application, published online.

Balon, E.K. (1975): Reproductive guilds of fishes: a proposal and definition. Journal of the Fisheries Research Board Canada, 32: 821–864.

Balon, E.K. (1990): Epigenesis of an epigeneticist: the development of some alternative concepts on the early ontogeny and evolution of fishes. Guelph Ichthyology Rev., 1: 1–42.

Bams, R.A. (1969): Adaptations in sockeye salmon associated with incubation in stream gravels. In: T.G. Northcote (editor). Symposium on Salmon and Trout in Streams. Vancouver, B.C., University of British Columbia: 71-87.

Banscher E. (1976): Gesetzmaeßigkeiten der Kolmationsentwicklung, Wasserwirtschaft, Wassertechnik, Berlin, 9, 320-323.

Baron, J.S., Poff, N.L., Angermeier, P.L., Dahm, C.N., Gleick, P.H., Hairston, N.G., Jackson, R.B., Johnston, C.A., Richter, B.D. & A.D. Steinman (2002): Meeting ecological and societal needs for freshwater. Ecological Applications, 12: 1247–1260.

Barrett, G.W., Peles, J.D. & E.P. Odum (1997): Transcending processes and the levels of organisation concept. Bioscience, 47: 531–535.

Barry, S. & J. Elith (2006): Errors and Uncertainty in habitat models. Journal of Applied Ecology, 43: 413–423.

Bartholow, J.M., Laake, J.L., Stalnaker, C.B. & S. Williamson (1993): A salmonid population model with emphasis on habitat limitations. Rivers, 4: 265–279.

Bartholow, J.M. (1996): Sensitivity of a salmon population model to alternative formulations and initial conditions. Ecological Modeling, 88 (1–3), 215–226.

Baveye, P.M., Vandevivere, P., Hoyle, B.L., De Leo, P.C. & D.S. De Lozada (1998): Environmental impact and mechanisms of the biological clogging of saturated soils and aquifer materials. Critical Reviews in Environmental Science and Technology, 28: 123–191.

Bayley, P.B. & H.W. Li (1996): Riverine Fishes, in: Petts, G. & P. Calow (eds.): River Biota. Blackwell Science, Oxford: 92–122.

Bechteler, W. (2008): Sediment Sources and Transport Processes. ALPRESERV, Sustainable Sediment Management of Alpine Reservoirs considering economic and ecological aspects, Volume 2, ISSN: 1862–9636.

Becker, C.D. & A.D. Neitzel (1985): Assessment of intergravel conditions influencing egg and alevin survival during salmonid redd dewatering. Environmental Biology of Fishes, 12: 3646.

Beecher, H.A., Caldwell, B.A., & S.B. Demond (2002): Evaluation of depth and velocity preferences of juvenile coho salmon in Washington streams. North American Journal of Fisheries Management, 22(3): 785–795.

Beer, W.N. & J.J. Anderson (1997): Modeling the growth of salmonid embryos. Journal of Theoretical Biology, 189: 297–306.

Bennett, J.P. & C.F. Nording (1977): Simulation of sediment transport and armouring. Hydrological Science Bulletin, XXII(4): 555–569.

Bergkamp, G., McCartney, M., Dugan, P., McNeely, J. & M. Acreman (2000): Dams, Ecosystem Functions and Environmental Restoration. Thematic Review II.1, prepared as an input to the World Commission on Dams, Cape Town.

Beschta, R.L. & W.L. Jackson (1979): The intrusion of fine sediments into a stable gravel bad, Journal of Fisheries Research, 36: 204-210.

Bettess, R. (2008): Sediment Transport & Alluvial Resistance in Rivers. R&D Technical Report W5i 609, Department of Environment, Food and Rural Affairs, ISBN: 978–1–84432–913–7.

Beyer, W. & E. Banscher (1975): Zur Kolmation der Gewaesserbetten bei der Uferfiltratgewinnung. Z. Angew. Geol., 12: 565–570.

Beyer, H.L., Haydon, D.T., Morales, J.M., Frair, J.L., Hebblewhite, M., Mitchell, M. & J. Matthiopolos (2010): The interpretation of habitat preference metrics under use–availability designs. Philosophical Transaction of the Royal Society, 365: 2245–2254.

Billard, R. & J.O.T. Jensen (1996): Gamete removal, fertilization and incubation, in: Pennell, W. & B.A. Barton (eds.): Principles of salmonid culture. Elsevier Science Publishers Ltd., Amsterdam: 291–364.

Bisantino, T., Gentilee, F., Milella, P., & G.T. Liuzzi (2010): Effect of time scale on the performance of different sediment transport formulas in a semiarid region. Journal of Hydraulic Engineering, ASCE, 136(1): 56–61.

Bjornn T.C. (1968): Survival and emergence of trout and salmon fry in various gravelsand mixtures. Pages 80-88 In: Logging and salmon: proceedings of a forum. America Institute of Fishery Research Biologists, Alaska District, Juneau, AK

Bjornn, T.C. & D.W. Reiser (1991): Habitat requirements of salmonids in streams. In: Meehan, W.R. Influences of forest and rangeland management of salmonid fishes and their habitats. Bethesda, MD, American Fisheries Society: 83–138.

Blohm, H.P., Gaumert D. & M. Kaemmerseit (1994): Leitfaden fuer die Wieder- und Neuansiedlung von Fischarten. Binnenfischerei in Niedersachsen.

Bockelmann, B.N., Fenrich, E.K., Lin, B. & R.A. Falconer (2004): Development of an ecohydraulics–model for stream and river restoration. Ecol. Eng. 2004, 22(4–5): 227–235.

Bonada, N., Prat, N., Resh, V.H. & B. Statzner (2006): Developments in aquatic insect biomonitoring: a comparative analysis of recent approaches. Annual Review of Entomology, 51: 495–523.

Borchardt, D. & M. Pusch (2009): The ecology of the hyporheic zone of running waters. Advances in Limnology, 61: 224 pp.

Boulton, A.J., Findlay, S., Marmonier, P., Stanley, E.H. & H.M. Valett (1998): The functional significance of the hyporheic zone in streams and rivers. Annual Review of Ecology and Systematics, 29: 59–81.

Boulton, A.J. (2007): Hyporheic rehabilitation in rivers: restoring vertical connectivity. Freshwater Biology, 52: 632–650.

Boumans, R., Costanza, R., Farley, J., Villa, F. & M. Wilson (2002): Modeling the dynamics of the integrated earth system and the value of global ecosystem services using the GUMBO model. Ecological Economics, 41: 529–560.

Bovee, K.D. (1982): A guide to stream analysis using the insteam flow incremental methodology. Instream Flow Information Paper No.: 12, FWS/OBS 82/26, U.S. Fish and Wildlife Service.

Bovee, K.D. (1986): Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology. Instream Flow Information Paper No.: 21, US Fish and Wildlife Service, Biologic Report, 86(7).

Bovee, K.D., Lamb B.L., Bartholow, J.M., Stalnaker, C.B., Taylor, J. & J. Henriksen (1998): Stream habitat analysis using the instream flow incremental methodology. U.S. Geological Survey Information and Technology Report 1998–0004: 130 pp.

Brandt, S.A. (2000): Classification of geomorphological effects downstream of dams. Catena, vol. 40 (4): 375–401 pp.

Bretschko, G. & W.E. Klemens (1986): Quantitative methods and aspects in the study of the interstitial fauna of running waters. Stygologia, 2: 297–316.

Brierley, G.J. & K.A. Fryirs (2005): Geomorphology and River Management, Applications of the River Styles Framework. Geomorphology and River Management, Blackwell Publishing, ISBN–13: 978–1–4051–1516–2.

Briggs, J.C. (1953): The behavior and reproduction of salmonid fishes in a small coastal stream. California Department of Fish and Game Fish, Bulletin 94.

Brodeur, P., Mingelbier, M. & J. Morin (2004): Impact of water discharge on fish reproduction measured using 2D numerical habitat in the St. Lawrence River, Canada. Proceedings of the Fifth International Symposium in Ecohydraulics: 237–241.

Brosse S. & S. Lek (2002): Relationships between environmental characteristics and the density of age–0 Eurasian perch (*Perca fluviatilis*) in the littoral zone of a lake: a nonlinear approach. Transactions of the American Fisheries Society, 131: 1033–1043.

Brunke, M. & T. Gonser (1997): The ecological significance of exchange processes between rivers and groundwater. Freshwater Biology, 37: 1–33.

Bui, M.D. & P. Rutschmann (2010): Numerical modelling of non–equilibrium graded sediment transport in a curved open channel. Computers and Geosciences, 36: 6.

Bunte, K. & S.R. Abt (2001): Sampling Surface and Subsurface Particle–Size Distributions in Wadable Gravel– and Cobble–Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring. General Technique Report RMRS–GTR–74, Fort Collins, CO.

Burns, D.C. & R.E. Edwards (1985): Embeddedness of salmonid habitat of selected streams on the Payette National Forest. USDA Forest Service, Payette National Forest, McCall, ID.

Cadenasso, M.L., Pickett S.T.A., Weathers K.C. & C.G. Jones (2003): A framework for a theory of ecological boundaries. BioScience, 53: 750–758.

Cao, Z., Day, R. & S. Egashira (2002): Coupled and decoupled numerical modeling of flow and morphological evolution in alluvial rivers. Journal of Hydraulic Engineering, ASCE, 128(3): 306–321.

Caissie, D. & D.J. Giberson (2003): Temporal variation of stream and intragravel water temperatures in an Atlantic salmon (*Salmo salar*) spawning area in Catamaran Brook (New Brunswick). Canadian Technical Report of Fisheries and Aquatic Sciences 2464, Fisheries and Oceans Gulf Fisheries Centre, Science Branch: Diadromous Fish Division.

Capra, H., Sabaton, C., Gouraud, V., Souchon, Y. & P. Lim (2003): A population dynamics model and habitat simulation as a tool to predict brown trout demography in natural and bypassed stream reaches. River Research and Applications, 19: 551–568.

Cardenas, M.B., (2008): Surface water–groundwater interface geomorphology leads to scaling of residence times. Geophysical Research Letters, 35: L08402.

Carling, P.A. & N.A. Reader (1982): Structure, composition and bulk properties of upland stream gravels. Earth Surface Processes and Landforms, 7: 349–365.

Carling, P.A. (1984): Deposition of fine and coarse sand in an open–work gravel bed. Canadian journal of fisheries and Aquatic Sciences, 41: 263–270.

Carman, P.C. (1956): Flow of Gases through Porous Media. Butterworths, Scientific Publications, London.

Capblanq, K. & P. Lavandier (1975): Primary production and oxygen budget in a stream of Central Pyrenees, Ann. Limnol., 11: 189-201.

Celik, I. & W. Rodi (1988): Modelling suspended sediment transport in non–equilibrium situations. Journal of Hydraulic Engineering, ASCE, 114: 1157–1191.

Chambers, J.S., Allen, G.H. & R.T. Pressey (1955): Research relating to study of spawning gravels in natural areas. Annual Report, Washington Department of Fisheries, Olympia.

Chanson, H. (2004): The Hydraulics of Open Channel Flow. 2nd Edition, Basic principles, sediment motion, hydraulic modelling, design of hydraulic structures, Elsevier Butterworth–Heinemann, ISBN 0–7506–5978–5.

Chapman, D.W. (1988): Critical review of variables used to define effects of fines in redds of large salmonids. Transactions of the American Fisheries Society 117: 1–21.

Chase, J.M. & M.A. Leibold (2002): Spatial scale dictates the productivity–diversity relationship. Nature, 415: 427–430.

Cheng, N.S. (1997): Simplified settling velocity formula for sediment particle. Journal of Hydraulic Engineering, ASCE, 123(2): 149–152.

Chevalier, B.E., Carson, C. & W.J. Miller (1984): Report of engineering and biological literature pertaining to the aquatic environment with special emphasis on dissolved oxygen and sediment effect on salmonid habitat. Colorado State University, Department of Agriculture and Chemical Engineering ARS Report No.: 5602–20813–008A.

Cocan, D., Zăhan, M., Mireşan, V., Constantinescu, R., Răducu, C., Neghela, B. & I. Sărmaş (2010): Studies on Some Productive and Reproductive Performance in Female Rainbow Trout (*Oncorhynchus Mykiss*) and Brown Trout (*Salmo Trutta Fario*) at Four Years of Age, in: Fiad–Telcişor Salmonids Complex. Bistriţa–Năsăud Count, Animal Science and Biotechnologies, 43(2).

Commission, E. (2000): Directive 2000/60/EC. Establishing a framework for community action in the field of water policy, Luxembourg: European Commission, PE-CONS 3639/1/100 Rev 1.

Conallin, J., Boegh, E. & J. Jensen (2010): Instream physical habitat modeling types: an analysis as stream hydromorphological modeling tools for EU water resource managers. Journal of River Basin Management, 8: 93–107, DOI: 10.080/1571521003715123.

Cooper, A.C. (1965): The effect of transported stream sediments on survival of sockeye and pink salmon eggs and alevins. Int. Pac. Salmon Comm. Bull. 18, New Westminister, British Columbia, Canada.

Cordonne, A.J. & D.O.N.W. Kelley (1961): The influences of inorganic sediments on aquatic life of streams. California Fish and Game, Sacramento, 47(2).

Crisp, D.T. (1981): A desk study of the relationship between temperature and hatching time for the eggs of five species of salmonid fishes. Freshwater Biology, 11: 361–368.

Crisp, D.T. & P.A. Carling (1989): Observations on siting, dimensions and structure of salmonid redds. Journal of Fish Biology, 34: 119–134.

Crisp, D.T. (1996): Environmental requirements of common riverine European salmonid fish species in fresh water with particular relevance to physical and chemical aspects. Hydrobiologia, 323: 201–221.

Crisp, D.T. (2000): Trout and Salmon, Ecology. Conservation and Rehabilitation, Blackwell Science, London.

Cui, Y., Wooster, J.K., Baker, P.F., Dusterhoff, S.R., Sklar, L.S. & W.E. Dietrich (2008): Theory of Fine Sediment Infiltration into Immobile Gravel Bed. Journal of Hydraulic Engineering, ASCE, 134(10): 1421–1429.

Cuthbertson, A.J.S. (2001): The motion of fine sand particles in turbulent open channel shear flows over porous bed conditions., Doctoral dissertation, University of Glasgow, Glasgow, Scotland.

Dahm, C.N. & H.M. Valett (1996): Hyporheic zones, in: Hauer, F.R. and Lamberti, G.A. (eds.): Methods in stream ecology. Academic Press, San Diego, California: 53–74 pp.

Dale, V.H. & S.C. Beyeler (2001): Challenges in the development and use of ecological indicators. Ecological Indicators, 1: 3–10.

Darby, S.E. & M.J. van de Wiel (2003): Models in Fluvial Geomorphology, in: Kondolf G.M. & H. Piégay: Tools in Fluvial Geomorphology. John Wiley & Sons Ltd, ISBN: 0–471–49142–X.

DaSilva, A.M.A.F. (1991): Alternate bars and related processes. PhD–Thesis, Queens University, Kingston Ontario, Canada.

Davis, J.C. (1975): Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species, a review. Canadian Journal of Fisheries and Aquatic Sciences, 32: 2295–2332.

De Groot, R.S. (1992): Functions of Nature: Evaluation of Nature in Environmental Planning, Management and Decision Making. Wolters–Noordhoff, Groningen.

De Groot, R.S., van der Perk, J., Chiesura, A. & S. Marguliew (2000): Ecological functions and socio–economic values of critical natural capital as a measure for ecological integrity and environmental health, in: Crabbe, P., Holland, A., Ryszkowski, L., Westra, L. (eds.): Implementing Ecological Integrity: Restoring Regional and Global Environmental and Human Health. NATO–Science Series, IV. Earth and Environmental Sciences, Vol. 1, Kluwer Academic Publishers, Dordrecht/Boston/London: 191–214 pp.

De Groot, R.S., Wilson, M.A. & R.M.J. Boumans (2002): A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics, 41: 393–408.

Dent, C.L., Schade, J.D., Grimm, N.B. & S.G. Fisher (2000): Subsurface influences on surface biology: 381–402, in: Jones, J.B. & P.J. Mulholland (eds.): Streams and ground waters. Academic Press, San Diego, California.

Descloux, S., Thibault, D., Philippe, M. & P. Marmonier (2010): Comparison of Different Techniques to Assess Surface and Subsurface Streambed Colmation with Fine Sediments. International Review of Hydrobiology, 95(6): 520–540.

Dietrich, W.E. (1982): Settling velocity of natural particles. Water Resources Research, 18(6): 1615–1626.

Diplas, P. & G. Parker (1992): Deposition and removal of fines in gravel bed streams, 313–329 in: Billi, R., Hey, D., Thorne, C.R. & P. Tacconi (eds.): Dynamics of gravel–bed rivers. Wiley, Chichester, UK.

Dirksmeyer, J. (2008): Untersuchungen zur OEkomorphologie der Laichhabitate von Lachsen und Meerforellen in Deutschland. Dissertation, Bibliothek Natur & Wissenschaft, Bd. 18, Verlag Natur und Wissenschaft, Solingen, Universitaet Koeln.

Dirksmeyer, J. & E. Brunotte (2009): Sediment textures and hydrogeomorphological characteristics of salmon and sea trout spawning habitats in Germany: A contribution to river ecology. Zeitschrift fuer Geomorphologie, 53(3): 319–334.

Doehing, M. (2002): Ecologial Assessment of Springs and Spring Brooks in the Swiss National Park: Combining Fieldwork with Geodesy and GIS, Diploma Thesis, Swiss Federal Institute for Environmental Science and Technology (EAWAG), Switzerland.

Doering, M. (2007): Environmental heterogeneity and respiration in a dynamic river corridor: structural properties and functional performance, PhD-Thesis, Swiss Federal Institute of Technology, Zuerich, ETH-No. 17046.

Doering, M., Uehlinger, U., Ackermann, T., Woodtli, M. & K. Tockner (2011): Spatiotemporal heterogeneity of soil and sediment respiration in a river floodplain mosaic (Tagliamento, Italy), Freshwater Biology, 56: 1297-1311.

Doessiger, R. (1987): Geologische Karte des Nationalpark (Geologische Spezialkarte Nr.122), Schweizerische Geologische Kommission, Kommission fuer wissenschaftliche Erforschung des Nationalparks und Landeshydrologie und –geologie.

Downes, B.J., Entwisle, T.J. & P. Reich (2003): Effects of Flow Regulation on Disturbance Frequencies and In–Channel Bryophytes and Macroalgae in some Upland Streams. River Research and Application, 19: 27–42.

Dumas, J. & S. Marty (2006): A new method to evaluate egg–to–fry survival of salmonids, trials with Atlantic salmon. Journal of Fish Biology, 68: 284–304

DVWK – Deutscher Verband fuer Wasserwirtschaft, Abwasser und Abfall e.V. (2003): Feststofftransportmodelle fuer Fließgewaesser. ATV–DVWK–Arbeitsbericht, Arbeitsgruppe: WW–2.4.

Eastman, K. (2004): Effects of Embeddedness on Fish Habitats: An Approach for Implementation in the Habitat Simulation Model CASiMiR. Master Thesis, Institute of Hydraulic Engineering, Universitaet Stuttgart.

Edmondson, W.T. & G.G. Winberg (1971): A manual on methods for the assessment of secondary productivity in fresh waters. Blackwell Scientific Publications, Oxford and Edinburgh.

Egger, G., Mader, H., Kucher T. & D. Bogner (2005): Watercourse-Habitat-Modelling – Illustrated by the Diverted River Section of the River Mur at the Power Station Laufnitzdorf/Mur, Styria, Austria, OEsterreichische Wasser- und Abfallwirtschaft, 57, 5-6,71-78.

Egger, G., Benjankar, R., Davis, L. & K. Jorde (2007): Simulated effects of dam operation and water diversion on riparian vegetation of the lower Boise river, Idaho, USA, In Harmonizing the Demands of Art and Nature in Hydraulics, 32nd Congress of IAHR, Venicy, Italy, 1-14.

Egiazaroff, I.V. (1965): Calculation of nonuniform sediment concentration. Journal of Hydraulics Division, ASCE, 91(HY4): 225–247.

Einstein, H.A., Anderson, A.G. & J.W. Johnson (1940): A distinction between bed load and suspended load. Transactions of the American Geophysical Union, 22: 628–632.

Einstein, H.A. (1950): The bed–load function for sediment transportation in open channel flows. Technical Bulletin No.: 1026, U.S. Department of Agriculture, Soil Conservation Service, Washington D.C., USA.

Einstein, H.A. (1968): Deposition of suspended particles in a gravel bed, Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, 94 (5): 1197–1205, New York.

Einum, S. & I.A. Fleming (2000): Selection against late emergence and small offspring in Atlantic salmon (*Salmo salar*). Evolution, 54: 628–639.

Elliott, J.M. (1976): Energy losses in the waste products of brown trout (*Salmo trutta* L.). Animal Ecology, 45: 561–580.

Elliott, J.M. (1981): Some aspects of thermal stress on freshwater teleosts, Pickering, A.D. (Editor): In Stress and Fish, 209–245. London: Academic Press.

Elliott, J.M. (1986): Spatial distribution and behavioural movements of migratory trout (*Salmo trutta*) in a Lake District stream. Journal of Animal Ecology, 55: 907–922.

Elliott, J.M. (1994): Quantitative ecology and the brown trout. Oxford University Press, Oxford: 286 pp.

Elliott, J.M. & M.A. Hurley (1998): A new functional model for estimating the maximum amount of invertebrate food consumed per day by brown trout (*Salmo trutta*). Freshwater Biology, 39: 339–349.

Engelund, F. & J. Fredsøe (1976): A sediment transport model for straight alluvial channels, Nordic Hydrology, 7: 293–306.

Engelund, F. & E. Hansen (1967): A Monograph on Sediment Transport in Alluvial Streams. Teknisk Vorlag, Copenhagen, Denmark.

Escobar–Arias, M.I. & G.B. Pasternack (2010): A hydrogeomorphic dynamics approach to assess in–stream ecological functionality using the functional flows model, part 1, model characteristics. River Research and Applications, 26(9): 1103–1128.

Esteve, M. (2005): Observations of spawning behaviour in Salmoninae: Salmo, Oncorhynchus and Salvelinus. Reviews in Fish Biology and Fisheries, 15: 1–21.

European Commission (2000): Directive 2000/60/EC: Establishing a framework for community action in the field of water policy. European Commission, Luxembourg, PE–CONS 3639/1/ 100 Rev 1.

Ferguson, R.I., Prestegaard, K.L. & P.J. Ashworth (1989): Influence of sand on hydraulics and gravel transport in meandering compound flows, Journal of Hydraulic Engineering, 119 (12): 1383-1399.

Ferreira, R.M.L. & A.H. Cardoso (2000): Modelling the morphologic evolution of graded sediment beds using multiple bed layers and diffusive flux concepts. Proceedings of 4th International Conference on Hydroscience and Engineering, Seoul, Korea.

Fine, T.L. (1999): Feedforward Neural Network Methodology. Springer, New York.

Finstad, A.G., Einum, S., Forseth, T. & O. Ugedal (2007): Shelter availability affects behavior, size–dependent and mean growth of juvenile Atlantic salmon. Freshwater Biology, 52: 1710–1718.

Fischer–Antze, T., Ruether, N., Olsen, N.R.B. & D. Gutknecht (2009): 3D modeling of non–uniform sediment transport in a channel bend with unsteady flow. Journal of Hydraulic Research, 47(5): 670–675.

Fischer, H., Pusch, M. & J. Schwoerbel (1996): Spatial distribution and respiration of bacteria in streambed sediments. Archiv fuer Hydrobiologie, 137: 281–300.

Fitzpatrick, F.A., Waite, I.R., D'Arconte P.J. & M.R. Meador (1998): Revised Methods for Characterizing Stream Habitat in the National Water–Quality Assessment Program. Report No.: 98–4052, U.S. Geological Survey, Raleigh, North Carolina.

Flanagan, J. (2003): The impacts of fine sediments and variable flow regimes on the habitat and survival of atlantic salmon (*salmo salar*) eggs, Master Thesis, University of New Brunswick.

Fluskey, R.D. (1989): An analysis of the gravels used by spawning salmonids in Ireland. Irish Fisheries Investigation Series A (Freshwater), 32: 1-14.

Franken, R.J.M., Storey, R.G. & D.D Williams (2001): Biological, chemical and physical characteristics of downwelling and upwelling zones in the hyporheic zone of a north–temperate stream. Hydrobiologia, 444: 183–195.

Frings, R.M., Kleinhans, M.G. & S. Vollmer (2008): Discriminating between pore–filling load and bed–structure load: a new porosity–based model, exemplified for the river Rhine. Sedimentology, 55: 1571–1593 pp.

Frings, R.M., Schuettrumpf, H. & S. Vollmer (2011): Verification of porosity predictors for fluvial sand–gravel deposits. Water Resources Research, 47: W07525.

Frissell, C.A., Liss, W.J., Warren, C.E. & M.D. Hurley (1986): A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management, 10: 199–214.

Frostick, L.E., Lucas, P.M. & L. Reid (1984): The infiltration of fine matrices into coarse grained alluvial sediments and its implication for stratigraphical interpretation. Journal of the Geological Society, 141: 955–965.

Garcìa, M.H. (2008): Sediment Transport and Morphodynamics, in García, M. H.: Sedimentation Engineering – Processes, Measurements, Modelling and Practice, American Society of Civil Engineers, ISBN-10: 0-7844-0814-9

Garcìa, M.H. & G. Parker (1991): Entrainment of bed sediment into suspension. Journal of Hydraulic Engineering, ASCE, 117 (4), 414–433.

Gard, M.F. (2006): Changes in salmon spawning and rearing habitat associated with river channel restoration. International Journal of River Basin Management, 4: 201–211.

Gard, M.F. (2009): Comparison of spawning habitat predictions of PHABSIM and River2D models. International Journal of River Basin Management, 7(1): 55–71.

Garland, R.D., Tiffan, K.F., Rondorf, D.W. & L.O. Clark (2002): Comparison of subyearling fall chinook salmon's use of riprap, revetments and unaltered habitats in Lake Wallula of the Columbia River. North American Journal of Fisheries Management, 22(4): 1283–1289.

Geist, D.R., Jones, J., Murray, V. & D.D. Dauble (2000): Suitability criteria analyzed at the spatial scale of redd clusters improved estimates of fall Chinook salmon (*Oncorhynchus tshawytscha*) spawning habitat use in the Hanford Reach, Columbia River. Canadian Journal of Fisheries and Aquatic Sciences, 57: 1636–1646.

Gibert, J., Stanford, J.A., Dole–Olivier, M.J. & J.V. Ward (1994): Basic attributes of groundwater ecosystems and prospects for research, in: Groundwater Ecology, Gibert J., Danielopol D., Stanford J.A. (eds.): Academic Press, San Diego, CA, 7–40.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J. & R.J. Nathan (2004): Stream hydrology: an introduction for ecologists, 2nd Edition. John Wiley & Sons LTD, West Sussex, England: 429 pp.

Gore, J.A. & J.M. Nestler (1988): Instream flow studies in perspective. Regulated Rivers, 2: 93–101.

Gozlan, R.E., Mastrorillo, S., Copp, G.H. & S. Lek (1999): Predicting the structure and diversity of young–of–the–year fish assemblages in large rivers. Freshwater Biology 41: 809–820.

Graf W.H. & E.R. Acaroglu (1968): A physical model for sediment transport in conveyance systems. Bulletin of the International Association of Scientific Hydrology, 13(3B).

Graf, W.L., Wohl, E., Sinha, T. & J.L. Sabo (2010): Sedimentation and sustainability of western American reservoirs. Water Resources Research, 46: W12535.

Greenwald, M.J., Bowden, W.B., Gooseff, M.N., Zarnetske, J.P., McNamara, J.P., Bradford, J.H. & T.R. Brosten (2008): Hyporheic exchange and water chemistry of two Arctic tundra stream of contrasting geomorphology. Journal of Geophysical Research (Biogeosciences), 11.

Greig, S.M., Sear, D.A. & P.A. Carling (2005): Fine sediment accumulation in salmon spawning gravels and the survival of incubating salmon progeny: implications for spawning habitat management. Science of the Total Environment, 344: 241–258.

Greig S.M., Sear, D.A. & P.A. Carling (2007): A review of factors influencing the availability of dissolved oxygen to incubating salmonid embryos. Hydrological Processes 21(3): 323–334, DOI: 10.1002/hyp.6188.

Griffith, M.B., Hill, B.H., McCormick, F.H., Kaufmann, P.R., Herlihy, A.T. & A.R. Delle (2005): Comparative application of indices of biotic integrity based on periphyton, macroinvertebrates and fish to southern Rocky Mountain stream. Ecological Indicators, 5: 117–136.

Grimm, V. (1999): Ten years of individual–based modelling in ecology: what have we learned and what could we learn in the future? Ecological Modelling, 115: 129–148.

Grimm, V. & S.F. Railsback (2005): Individual–based modeling and ecology. Princeton University.

Grost, R.T., Hubert, W.A. & T.A. Wesche (1991): Description of brown trout redds in a mountain stream, Transaction of the American Fisheries Society 120: 582-588.

Groot, C. (1996): Salmonid life histories, in: Pennell, W. & A. Bruce (eds.): Principles of Salmonid Culture. Elsevier, Amsterdam: 97–230.

Growns, I. (2004): A numerical classification of reproductive guilds of the freshwater fishes of south–eastern Australia and their application to river management. Fisheries Management and Ecology, 11: 369–377.

Guenter, A. (1971): Die kritische mittlere Sohlenschubspannung bei Geschiebemischungen unter Beruecksichtigung der Deckschichtbildung und der turbulenzbedingten Sohlschubspannungsschwan-kungen. PhD–Thesis, 4649, ETH Zuerich.

Guisan, A. & N.E. Zimmermann (2000): Predictive habitat distribution models in ecology. Ecological modelling, 135: 147–186.

Gutknecht, D., Blaschke, A.P., Schmalfuss, R., Sengschmitt, D., Steiner, K.H., Reichel, K.G., Feregyhazy, H., Herndl, G.J., Battin, T.J. & V. Dreher (1998): Kolmationsprozesse am Beispiel des Stauraumes Freudenau. Schriftenreihe der Forschung im Verbund, Bd. 44.

Hamilton, D.G., Ebersole, B.A., Smith, E.R. & P. Wang (2001): Development of a Large–Scale Laboratory Facility for Sediment Transport Research. Technical Report, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Hancock, P. (2002): Human impacts on the stream–groundwater exchange zone. Environmental management, 29: 761–781.

Harby, A., Baptist, M., Dunbar, M.J., & S. Schmutz (2004): COST Action 626: State–of–the–art in data sampling, modelling analysis and applications of river habitat modelling. European Aquatic Modelling Network.

Hardy, T.B. (1998): The future of habitat modeling and instream flow assessment technologies. Regulated Rivers, Research & Management: 405–420.

Hart, P.J.B. & J.D. Reynolds (2002): Handbook of Fish Biology and Fisheries. Blackwell Publishing, Oxford.

Harvey, J.W. & B.J. Wagner (2000): Quantifying hydrologic interactions between streams and their subsurface hyporheic zones, in: J.B. Jones & P.J. Mulholland (eds.): Streams and Ground Waters. Academic Press, San Diego, 2000: 3–44.

Haschenburger, J.K. & P. Roest (2009): Substrate indices as indicators of interstitial pore space in gravel–bed channels. River Research and Applications, 25(1): 98–105.

Hauer, C., Unfer, G., Schmutz, S. & H. Habersack (2007): The importance of morphodynamic processes at riffles used as spawning grounds during the incubation time of nase (*Chondrostoma nasus*). Hydrobiologia 579: 15–27.

Hauer, C., Unfer, G., Schmutz, S. & H. Habersack (2008): Morphodynamic effects on the habitat of Juvenile Cyprinids (*Chondrostoma nasus*) in a restored Austrian lowland river. Environ. Manage. 42 (2): 279–296.

Hauer, C., Unfer, G., Tritthart, M. & H. Habersack (2010): Effects of stream channel morphology, transport processes and effective discharge on salmonid spawning habitats. Earth Surface Processes and Landforms, 36(5): 672–685.

Hayes, J.W., Stark, J.D. & K.A. Shearer (2000): Development and test of a whole lifetime foraging and bioenergetics model for drift–feeding brown trout. Transactions of American Fisheries Society, 129: 315–332.

Hazen, A. (1892): Some Physical Properties of Sands and Gravels, with Special Reference to their Use in Filtration. 24th Annual Report, Massachusetts State Board of Health, Pub.Doc. No.: 34: 539–556.

Heggberget, T.G., Haukebø, T., Mork, J. & G. Stahl (1988): Temporal and spatial segregation of spawning in sympatric populations of Atlantic salmon, *Salmo salar* L. and brown trout, *Salmo trutta* L, Journal of Fish Biology 33: 347–356.

Heggenes, J. (1988): Substrate preferences of brown trout fry (*Salmo trutta*) in artificial stream channels. Canadian Journal of Fish and Aquatic Science 45: 1801–1806.

Heggenes, J. (1990): Habitat utilisation and preferences in juvenile Atlantic salmon (*Salmo salar*) in streams. Regulated Rivers, 5: 341–354.

Helfman, G.S., Collette, B.B., Facey, D.E. & B. Bowen (2009): The Diversity of Fishes. Biology, Evolution, and Ecology, 2nd Edition, Wiley & Blackwell, John Wiley & Sons Ltd., Publication, ISBN: 978–1–4051–2494–2.

Hendricks S.P. & D.S. White (2000): Stream and groundwater influences on phosphorus biogeochemistry, in: Jones, J.B. & P.J. Mulholland (eds.): Streams and Ground Waters: 221–235, Academic Press, San Diego.

Heywood, M.J.T. & D.E. Walling (2007): The sedimentation of salmonid spawning gravels in the Hampshire Avon catchment, UK: implications for the dissolved oxygen content of intragravel water and embryo survival. Hydrological Processes, 21(6): 770.

Hicks, D.M. & B. Gomez (2003): Sediment transport, in: Kondolf G.M. & H. Piégay (eds.): Tools in Fluvial Geomorphology. John Wiley & Sons Ltd, ISBN: 0–471–49142–X.

Higashino, M. & H.G. Stefan (2008): Near–bed turbulence models: Significance for diffusional mass transfer at the sediment/water interface. Journal of Hydraulic Research, 46(3): 291–300.

Hjulstrom, F. (1935): The Morphological Activity of Rivers as Illustrated by River Fyris. Bulletin ofthe Geological Institute, Uppsala, 25: Chapter 3.

Hirano, M. (1971): River bed degradation with armouring. Journal of the Japan Society of Civil Engineers, 3(2): 55–65.

Hu, H.M. & K.H. Wang (1999): Entrainment function of suspended sediment in open channels. International Journal of Sediment Research, 14 (3): 1–8.

Huettel, M., Røy, H., Precht, E. & S. Ehrenhauss (2003): Hydrodynamical impact on biogeochemical processes in aquatic sediments. Hydrobiologia, 494: 231–236.

Hung, C.C., Gong, G.C., Chiang, K.P., Chen, H.Y. & K.M. Yeager (2009): Particulate carbohydrates and uronic acids in the northern East China Sea. Estuarine, Coastal and Shelf Science 84: 565–572.

Hunziker, R.P. (1995): Fraktionsweiser Geschiebetransport. Mitteilungen der Versuchsanstalt fuer Wasserbau, Hydrologie und Glaziologie, 138, Eidgenoessische Technische Hochschule (ETH), Zuerich, Switzerland.

Humpesch, U. H. (1985): Inter- and intra-specific variation in hatching success and embryonic development of five species of salmonids and *Thymallus thymallus*, Archiv fuer Hydrobiologie 104, 129–144.

Hupp, C.R., Noe, G.B. & E.R. Schenk (2010): Floodplains, Equilibrium, and Fluvial Geomorphic Impacts of Human Alterations. 2nd Joint Federal Interagency Conference, Las Vegas, USA.

Ingendahl, D. (1999): Der Reproduktionserfolg von Meerforelle (*Salmo trutta* L.) und Lachs (*Salmo salar* L.) in der Korrelation zu den Milieubedingungen des hyporheischen Interstitials, Dissertation, Universitaet Koeln, 172 S.

Ingendahl, D. (2001): Dissolved oxygen concentration and emergence of sea trout fry from natural redds in tributaries of the river Rhine. Journal of Fish Biology, 58: 325–341.

Irvine, J., R., Jowett, I.G. & D. Scott (1987): A test of the Instream Flow Incremental Methodology for underyearling rainbow trout (*Salmo gairdnerii)*, in experimental New Zealand streams. New Zealand Journal of Marine and Freshwater Research, 21(1): 35–40.

Ishaku, J.M., Gadzama, E.W. & U. Kaigama (2011): Evaluation of empirical formulae for the determination of hydraulic conductivity based on grain–size analysis. Journal of Geology and Mining Research, 3: 105–113.

Jackson, L.E., Kurtz, J.C. & W.S. Fisher (2000): Evaluation guidelines for ecological indicators. EPA/620/R–99/005 Research Triangle Park, NC, U.S. Environmental Protection Agency, Office of Research and Development.

Jacobs J. (1974): Quantitative measurement of food selection, Oecologia 14: 413–417.

Jakob, C. (2001): The effects of artificial floods on the ecology of a regulated river, Diploma Thesis, Swiss Federal Institute of Technology (ETH), Swiss Federal Institute for Environmental Science and Technology (EAWAG), Zuerich

Jakob, C., Robinson, C.T. & U. Uehlinger (2003): Longitudinal effects of experimental floods on stream benthos downstream from a large dam. Aquatic Sciences, Research Across Boundaries, 65: 223–231, DOI: 10.1007/s00027–003–0662–9.

Jakobsen, T., Fogarty, M.J., Megrey, B.A. & E. Moksness (2009): Fish Reproductive Biology: Implications for Assessment and Management. Wiley–Blackwell, Oxford, UK.

Jankowski, J.A., Malcherek, A. & W. Zielke (1994): Numerical modeling of sediment transport processes caused by deep sea mining discharge. Proceedings of OCEANS 94 Conference, Brest,IEEE/SEE, 3: 269–276.

Jiménez, J.A. & O.S. Madsen (2003): A simple formula to estimate settling velocity of natural sediments. Journal of Waterway, Port, Coastal and Ocean Engineering 129(2): 70–78, Reston, Virginia.

Johnson, R.A. (1980): Oxygen transport in salmon spawning gravels. Canadian Journal of Fisheries Aquatic Science, 37: 155–162.

Jones, J.B., Fisher S.G. & N.B. Grimm (1995): Vertical hydrologic exchange and ecosystem metabolism in a Sonoran Desert stream, Ecology 76: 942-952.

Jones, R.E., Petrell, R.J. & D. Pauly (1999): Using modified length–weight relationships to assess the condition of fish. Aquacultural Engineering, 20: 261–276.

Jongman, R.H.G., Ter Braak, C.J.F. & O.F.R van Tongeren (1995): Data analysis in community and landscape ecology. Cambridge University Press, Cambridge.

Jordan, R.M. & K.F. Beland (1981): Atlantic salmon spawning and evaluation of natural spawning success, Atlantic Sea-Run Salmon Commission, Augusta, 26 pp.

Jorde, K. (1996): OEkologisch begruendete, dynamische Mindestwasserregelungen bei Ausleitungskraftwerken. Mitteilungen des Instituts fuer Wasserbau, Universitaet Stuttgart, Heft 90, Eigenverlag, Institut fuer Wasserbau der Universitaet Stuttgart, Stuttgart.

Jørgensen, S.E. & G. Bendoricchio (2001): Fundamentals of Ecological Modelling. 3rd Edition, Elsevier Science Ltd. New York, ISBN: 0–080–44015–0.

Jonsson, B. & N. Jonsson (2009): A review of the likely effects of climate change on anadromous Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*), with particular reference to water temperature and flow. Journal of Fish Biology, 75: 2381–2447.

Jowett, I. (1997): Instream flow methods: a comparison of approaches. Regulated Rivers, Research & Management, 13: 115–127.

Jowett, I.G. (2003): Hydraulic constraints on habitat suitability for benthic invertebrates in gravel–bed rivers. River Research and Applications, 19: 495–507.

Jowett, I.G. & A.J.H. Davey (2007): A comparison of composite habitat suitability indices and generalized additive models of invertebrate abundance and fish presence–habitat availability. Transactions of the American Fisheries Society, 136(2): 428–444.

Jungwirth, M. & H. Winkler (1984): The temperature dependence of embryonic development of grayling (*Thymallus thymallus*), Danube salmon (*Hucho hucho*), Arctic char (*Salvelinus alpinus*) and brown trout (*Salmo trutta fario*). Aquaculture, 38: 315–327.

Jungwirth, M., Muhar, S. & S. Schmutz (2000): Fundamentals of fish ecological integrity and their relation to the extended serial discontinuity concept. Hydrobiologia, 422/423: 85–97.

Kachel, N.B. & J.D. Smith (1989): Sediment transport and deposition on the Washington continental shelf, in: M. R. & Hickey, B. M., (eds.): Coastal Oceanography of Washington and Oregon Landry. Elsevier, Amsterdam: 287–348 pp.

Kaeser, D.H., Binley, A., Heathwaite, A.L. & S. Krause (2009): Spatio–temporal variations in hyporheic flow in a riffle–step–pool sequence. Hydrological Processes, 23: 2138–2149.

Kamler, E. (1992): Early life history of fish, an energetics approach. Chapman and Hall: 267 pp.

Kantoush, S.A., Sumi, T., Kubota, A. & T. Suzuki (2010): Impacts of Sediment Replenishment Below Dams on Flow and Bed Morphology of Rivers Channel and Rivers Mouth. First International Conference on Coastal Zone Management of River Deltas and Low Land Coastlines, Alexandria.

Karim, F. (1998): Bed material discharge prediction for nonuniform bed sediments. Journal of Hydraulic Engineering, ASCE, 124(6): 597–604.

Karr, J.R. (1993): Defining and assessing ecological integrity: beyond water quality. Environmental Toxicology and Chemistry, 12: 1521–1531.

Kelly F., Champ, T., McDonnell, N., Kelly-Quinn, M., Harrison, S., Arbuthnott, A., Giller, P., Joy, M., McCarthy, K., Cullen, P., Harrod, C., Jordan, P., Griffiths, D. & R. Rosell (2007): Investigation of the relationship between fish stocks, ecological quality ratings (q- values), environmental factors and degree of eutrohpication, Environmental Protection Agency, Ireland.

Kent, M. (2011): Infectious diseases and potential impacts on survival of Fraser River sockeye salmon, Cohen Commission Tech. Rept. 1: 58p. Vancouver, B.C.

Kerle, F., Zoellner, F., Schneider, M., Boehmer, J., Kappus, B. & M.J. Baptist (2002): Modelling of long–term Fish Habitat Changes in Restored Secondary Floodplain Channels of the River Rhine. 4th Symposium of Ecohydraulics, Cape Town, South Africa.

Khorram, S. & M. Ergil (2010): A Sensitivity Analysis Of Total–Load Prediction Parameters In Standard Sediment Transport Equations. Journal of the American Research Association, 46(6): 1091–115.

Killeen, S. (2009): The Hyporheic Handbook, a handbook on the groundwater surface, water interface and hyporheic zone for environment managers. Environment Agency Science report No.: SC050070. Environment Agency, Bristol, UK. ISBN: 978–1–84911–131–7.

King, R.T. (1966): Wildlife and man. New York Conservationist 20 (6), 8–11, in: Bailey, I.A., Elder, W., McKinney, T.B.: Readings in Wildlife Conservation, The Wildlife Society, Washington, DC, 1974.

Kirchhofner, A. (2001): Zur Bedeutung eines intakten Geschiebehaushalts fuer die Biologie in Fließgewaessern. Unveroeffentlichtes Skript: 2.

Klamt, R.R. (1976): The effects of coarse granitic sand on the distribution and abundance of salmonids in the central Idaho Batholith. Master Thesis, University of Idaho, Moscow.

Klemetsen, A., Amundsen, P.A., Dampson, B., Jonsson, B., Jonsson, N., O'Connel, M.F. & E. Mortensen (2003): Atlantic salmon (*Salmo salar L.*), brown trout, (*Salmo trutta L.*) and Arctic charr (*Salvelinus alpinus L.*): a review of aspects of their life histories. Ecology of Freshwater Fish, 12: 1–59.

Klimant, I., Meyer, V. & M. Kuh (1995): Fiber-optic microsensors, a new tool in aquatic biology. Limnology and Oceanography 40: 1159–1165.

Knopf, C.M. (2010): A permeability study on salmonid spawning riffles in the little river drainage and cañon creek in Northern Humboldt County, California, Master Thesis, Humboldt State University.

Komar, P.D. & C.E. Reimers (1978): Grain shape effects on settling rates. Journal of Geology, 86: 193–209.

Kondolf, G.M. & M.G. Wolman (1993): The sizes of salmonid spawning gravels. Water Resources Research, 29: 2275–2285.

Kondolf, G.M. (1997): Hungry Water: Effects of Dams and Gravel Mining on River Channels. Environmental Management, 21(4): 533–551.

Kondolf, G.M. (2000): Assessing salmonid spawning gravels. Transactions of the American Fisheries Society, 129: 262–281.

Kondolf, G.M., Angermeier, P., Cummins, K., Dunne, T., Healey, M., Kimmerer, W., Moyle, P.B., Murphy, D., Patten, D., Railsback, S., Reed, D., Spies, R. &R. Twiss (2008): Prioritizing river restoration: Projecting cumulative benefits of multiple projects: an example from the Sacramento-San Joaquin River system in California, Environmental Management , 42: 933-945.

Kopecki, I. (2008): Calculational approach to FST-hemispheres for multiparametrical Benthos Habitat modelling. Dissertation, Mitteilungen des Instituts fuer Wasserbau, Heft 169, Universitaet Stuttgart, Eigenverlag.

Kryzhanovsky, S.G. (1948): Ecological groups of fishes and principles of their development. Izv. Tikhookean. Nauchno–lsshd. Inst. Ryhn. Khoz. Okean., 27.

Lapointe, M.F., Bergeron, N.E., Bérubé, F., Pouliot, M.A. & P. Johnston (2004): Interactive effects of substrate sand and silt contents, redd–scale hydraulic gradients, and interstitial velocities on egg–to–emergence survival of Atlantic Salmon (*Salmo salar*), Canadian Journal of Fisheries and Aquatic Sciences, 61: 2271–2277.

Leathwick, J.R., Rowe, D., Richardson, J., Elith, J., & T. Hastie (2005): Using multivariate adaptive regression splines to predict the distributions of New Zealand's freshwater diadromous fish. Freshwater Biology, 50(12): 2034–2052.

Leclerc, M.A., St–Hilaire, A., & J.A. Bechara (2003): State–of–the–art and perspectives on habitat modelling. CanadianWater Resources Journal, 28(2): 153–172.

Lehmann, A., Overton, J.M & M.P. Austin (2002): Regression models for spatial prediction: their role for biodiversity and conservation. Biodiversity and Conservation, 11: 2085–2092.

Lek, S., Delacoste, M., Baran, P., Dimopoulos, I., Lauga, J., & S, Aulagnier (1996): Application of neural networks to modeling nonlinear relationships in ecology. Ecological Modelling, 90(1): 39–52.

Lek, S. & J.F. Guegan (1999): Artificial neural networks as a tool in ecological modelling, an introduction. Ecological Modelling, 120(2–3): 65–73.

Lewis, W.K., Gilliland, E.R., & W.C. Bauer (1949): Characteristics of fluidized particles, Industrial and Engineering Chemistry, 41: 1104–1117.

Lindroth, A. (1942): Sauerstoffverbrauch der Fische. 11 Verschiedene Entwicklungs– und Altersta-dien vom Lachs und Hecht. Zeitung fuer vergleichende Physiologie, 29: 583–594.

Lisle, T.E. (1989): Sediment Transport and Resulting Deposition in Spawning Gravels, North Coastal California. Water Resources Research, 25(6): 1303–1319.

Lisle, T.E. & J. Lewis (1992): Effects of sediment-transport on survival of salmonid embryos in a natural stream: a simulation approach, Canadian Journal of Fisheries Aquatic Science, 49:2337-2344.

Lotspeich, F.B. & F.L. Everest (1981): A new method for reporting and interpreting textural composi-tion of spawning gravel, U.S. Department of Agriculture, Forest Service, Research Note, 139: 11 pp.

Louhi, P., Maeki–Petaeys, A. & J. Erkinaro (2008): Spawning habitat of Atlantic salmon and brown trout: general criteria and intragravel factors. River Research and Applications, 24: 330–339.

LUBW (2005): Mindestabfluesse in Ausleitungsstrecken, Anhang 3: Anforderungsprofile fuer Indikator-Arten, Landesanstalt fuer Umweltschutz Baden-Wuerttemberg, ISBN:3-88251-297-0.

MacKenzie, C. & J.R. Moring (1988): Estimating survival of Atlantic salmon during the intergravel period. North American Journal Fisheries Management. 8, 45–49.

Maddock, I. (1999): The importance of physical habitat assessment for evaluating river health. Freshwater Biology, 41: 373–391.

Maddock, I.P., Smolar–Žvanut, N. & G. Hill, (2008) The effect of flow regulation on the distribution and dynamics of channel geomorphic units (CGUs) and implications for Marble Trout (*Salmo marmoratus*) spawning habitat in the Soča River, Slovenia. Earth and Environmental Science, 4.

Mahesh, K., Constantinescu, G. & P. Moin (2004): A numerical method for large eddy simulation in complex geometries. Journal of Computational Physics, 197: 215–240.

Malcolm, I.A., Soulsby, C., Youngson, A. & J. Petry (2003): Heterogeneity in ground water surface water interactions in the hyporheic zone of a salmonid spawning stream: towards integrating hydro-metric and tracer approaches. Hydrological Processes, 17: 601–617.

Malcolm, I.A., Soulsby, C. & A.F. Youngson (2006): High frequency logging technologies reveal state dependant hyporheic process dynamics: implications for hydroecological studies. Hydrological Processes, 20: 615–622.

Malcolm, I.A., Youngson, A.F., Greig, S. & C. Soulsby (2008): Hyporheic influences on spawning success, in: Sear, D.A., DeVries, P. (eds.): Salmon Spawning Habitat in Rivers: Physical Controls, Biological Responses and Approaches to Remediation. American Fisheries Society: 225–248.

Marmonier, P., Delettre, Y., Lefebvre, S., Guyon, J. & A.J. Boulton (2004): A simple technique using wooden stakes to estimate vertical patterns of interstitial oxygenation in the bed of rivers. Archiv fuer Hydrobiologie, 160, 133–143.

Maquaire, O., Ritzenthaler, A., Fabre, D., Ambroise, B., Thiery, Y., Truchet, E., Malet, J.P. & J. Monnet (2002): Caractérisation des profils de formations superficielles par pénétrométrie dynamique à énergie variable: application aux marnes noires de Draix. Geosci., 334: 835–841.

May, R.J., Maier, H.R., Dandy, G.C., & T. Fernando (2008): Non–linear variable selection for artificial neural networks using partial mutual information. Environmental Modelling & Software, 23(10–11): 1312–1326.

McBain, S. & W.J. Trush (2001): Spawning Gravel Composition and Permeability within the Garcia River Watershed. Fisheries, Vol. 95518.

McCuddin, M.E. (1977): Survival of salmon and trout embryos and fry in gravel–sand mixtures. Master thesis, University of Idaho, Moscow.

McDonald, R., Nelson, J., Paragamian, V. & G. Barton (2010): Modeling the Effect of Flow and Sediment Transport on White Sturgeon Spawning Habitat in the Kootenai River, Idaho. Journal of Hydraulic Engineering, 136(12): 1077.

McNeil, W.J. & W.J. Ahnell (1960): Measurement of gravel composition of salmon stream beds. University of Washington, Fisheries Research Institute. Circular Number 120. Seattle, Washington.

Merz, J.E., Setka, J.D., Pasternack, G.B. & J.M. Wheaton (2004): Predicting benefits of spawning–habitat rehabilitation to salmonid (Oncorhynchus spp.) fry production in a regulated Californian River. Canadian Journal of Fisheries and Aquatic Science, 61: 1433–1446.

Meyer C.B. (2003): The importance of measuring biotic and abiotic factors in the lower egg pocket to predict coho salmon egg survival, Journal of Fish Biology 62: 534–548.

Meyer, E.I., Niepagenkemper, O., Molls, F. & B. Spaenhoff (2008): An experimental assessment of the effectiveness of gravel cleaning operations in improving hyporheic water quality in potential salmonid spawning areas. River Research and Application, 24: 119–131, DOI: 10.1002/rra.1051.

Meyer–Peter, E. & R. Mueller (1948): Formulas for bed–load transport. Proceedings of 2nd IAHR Congress, Stockholm Sweden.

Mikos, M. (2005): Sediment Transport, Water Encyclopedia: 417–421.

Milhous, R.T., Updike M.A. & D.M. Schneider (1989): Physical Habitat Simulation Reference Manual. Version II. Instream Flow Information, Paper No.: 26, Biological Report, 89(16). US Fish and Wildlife Service, Fort Collins, Colorado.

Minshall, G.W. (1988): Stream ecosystem theory: a global perspective. Journal of North American Benthos Society, 7(4): 263–288.

Moir, H.J., Gibbins, C.N., Soulsby, C. & A.F. Youngson (2005): PHABSIM modelling of Atlantic salmon spawning habitat in an Upland stream: testing the influence of habitat suitability Indices on model output. River Research and Applications, 21: 1021–1034.

Molnar, P. (2010): Fluvial Systems, Script Edition Autumn Semester 2010, Institute of Environmental Engineering, ETH Zuerich.

Montgomery, D.R. & J. M. Buffington (1998): Channel processes, classification and response, in: Naiman, R.J. & R.E Bilby (eds.): River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer–Verlag, New York: 13–42 pp.

Morrice, J.A., Valett, H.M., Dahm, C.N. & M.E. Campana (1997): Alluvial characteristics, groundwater–surface water exchange and hydrological retention in headwater streams. Hydrological Processes, 11: 253–267.

Mosselman, E. (2010): Modeling Sediment Transport And Morphodynamics Of Gravel–Bed Rivers. Proceedings of 7th Gravel–Bed Rivers Conference 2010, Tadoussac, Canada.

Mouton, A.M., Schneider, M., Kopecki, I., Goethals, P.L.M. & N. De Pauw (2006): Application of MesoCASiMiR: Assessment of Baetis rhodani habitat suitability, in: Voinov, A., Jakeman, A.J. & A.E. Rizzoli, (eds.): Proceedings of the iEMSs Third Biennial Meeting: "Summit on Environmental Modelling and Software". International Modelling and Software Society, Burlington, USA, CD–ROM publication.

Mouton, A. (2008): A critical analysis of performance criteria for the evaluation and optimisation of fuzzy species distribution models. PhD–Thesis, University of Gent, Belgium.

Mull, K.E. & M.A. Wilzbach (2007): Selection of spawning sites by coho salmon in a northern California stream, North American Journal of Fisheries Management 27: 1343-1354.

Muerle, U. (2000): Morphologie und Habitatstruktur in der Ausleitungsstrecke einer alpinen Stauhaltung. Diploma thesis, University Karlsruhe, Germany.

Muhar, S., Muhar, A., Schmutz, S., Wimmer, R., Wiesbauer, H., Hozang, B., Imhof, G. & P. Tschemernig (1993): Ausweisung naturnaher Fließgewaesserabschnitte in OEsterreich. Vorstudie, Blaue Reihe BM Umwelt, Jugend u. Familie, Wien: 175 pp.

Murchie, K.J., Hair, K.P.E., Pullen, C.E., Redpath, T.D., Stephens, H.R. & S.J. Cooke (2008): Fish response to modified flow regimes in regulated rivers: research methods, effects and opportunities. River Research and Applications, 24: 197–217.

Neill, C.R. (1967): Mean velocity criterion for scour of coarse uniform bed material. Proceedings 12th IAHR Congress, Fort Collins, 3: 46–54.

Nelson, J.M., Bennet, J.P. & S.M. Wiele (2003): Flow– and Sediment–Transport Modelling, in: Kondolf, G.M. & H. Piégay: Tools in Fluvial Geomorphology, John Wiley & Sons Ltd, ISBN: 0–471–49142–X.

Nicols, G. (2009): Sedimentology and Stratigraphy. Second Edition, Wiley Blackwell, ISBN 978–1–4051–9379–5.

Niepagenkemper, O. & E.I. Meyer (2002): Messungen der Sauerstoffkonzentration in Flusssedimenten zur Beurteilung von potentiellen Laichplaetzen von Lachs und Meerforelle. Veroeffentlichungen des Landesfischereiverbandes Westfalen und Lippe e.V. 2: 1–87.

Nilsson, C., Reidy, C.A., Dynesius, M. & C. Revenga (2005): Fragmentation and Flow Regulation of the World’s Large River Systems. Science, 308: 405–407.

Noack, M. (2005): Application, Validation and Optimization of modelling approaches for the implementation of morphodynamic processes in habitat modelling. Diploma Thesis, Institute of Hydraulic Engineering, Universitaet Stuttgart.

Noack, M., Eisner, A., Wieprecht, S. & M. Schneider (2008): Auswirkungen von Stauraum–Spuelungen auf die Fließgewaesseroekologie. KW Korrespondenz Wasserwirtschaft 2008, Nr. 6: 320–325.

Noack, M., Schneider, M. & S. Wieprecht (2010): Aquatic habitat simulation tools: Univariate preference functions versus multivariate fuzzy–logic. Proceeding of International Symposium on Ecohydraulics, 2010, Seoul.

NRC (National Research Council) (2000): Ecological Indicators for the Nation, Committee to Evaluate Indicators for Monitoring Aquatic and Terrestrial Environments. Board on Environmental Studies and Toxicology, Water Science and Technology Board, National Academy Press, Washington, DC.

Odong, J. (2008): Evaluation of Empirical Formulae for Determination of Hydraulic Conductivity based on Grain–Size Analysis. The Journal of American Science, 4(1): 1–6.

Ojanguren, A.F. & F. Braña (2003): Thermal dependence of embryonic growth and development in brown trout. Journal of Fish Biology, 62: 580–590.

Oksanen, J. & P.R. Minchin (2002): Continuum theory revisited: what shape are species responses along ecological gradients? Ecological Modelling, 157: 119–129.

Olden, J.D. & D.A. Jackson (2002): Illuminating the ‘black box’: understanding variable contributions in artificial neural networks. Ecological Modelling, 154: 135–150.

Olsen, N.R.B. (1991): A numerical model for simulation of sediments in water intakes. PhD–Thesis, Norwegian Institute of Technology, Trondheim.

Olsen, N.R.B. (2010): SSIIM Users’ Manual. Version May 2010. The Norwegian University of Science and Technology: http://folk.ntnu.no/nilsol/ssiim/manual3.pdf.

Orghidan, T. (1959): Ein neuer Lebensraum des unterirdischen Wassers: Der hyporheische Biotop. Archiv fuer Hydrobiologie, 55: 392–414.

Orton, P.M. & G.C. Kineke (2001): Comparing Calculated and Observed Vertical Suspended–Sediment Distributions from a Hudson River Estuary Turbidity Maximum, Estuarine, Coastal and Shelf Science 2001, 52: 401–410.

Ortlepp, J. & U. Muerle (2003): Effects of experimental flooding on fishes: The River Spoel, Swiss National Park. Aquatic Sciences, Research Across Boundaries, 65: 232–238, DOI: 10.1007/s00027–003–0666–5.

Ozaki, K., Isono, M., Kawahara, T., Iida, S., Kudo, T. & K. Fukuyama (2006): A mechanistic approach to evaluation of umbrella species as conservation surrogates. Conservation Biology, 20: 1507–1515.

Packman, A.I. & K.E. Bencala (2000): Modeling surfacesubsurface hydrological interactions in: Jones J.B. & P.J. Mulholland (eds.): Streams and Ground Waters. Academic Press, 45.

Papanicolaou, A., Elhakeem, M., Krallis, G. & S.J. Edinger (2008): Sediment transport modeling review, current and future developments. Journal of Hydraulic Engineering, 134(1): 1–14.

Parasiewicz, P. & M.J. Dunbar (2001): Physical habitat modelling for fish: a developing approach. Archiv fuer Hydrobiologie. Suppl., Large Rivers Vol.12, 135(2–4): 239–268.

Parasiewicz, P. & J.D. Walker (2007): Comparison of MesoHABSIM with two microhabitat models (PHAPSIM and HARPHA). River Research and Applications, 23(8): 904–923.

Park, Y.S., Grenouillet, G., Esperance, B. & S. Lek (2006): Stream fish assemblages and basin land cover in a river network. Science of the Total Environment, 365(1–3): 140–153.

Parker, G., Kilingeman, P.C. & D.G. McLean (1982): Bed load and size distribution in paved gravel–bed streams. Journal of Hydraulics Division, ASCE, 108(4): 544–571.

Pasternack, G.B., Wang, C.L. & J.E. Merz (2004): Application of a 2D hydrodynamic model to design of reach–scale spawning gravel replenishment on the Mokelumne River, California. River Research and Applications 20: 205–225.

Patankar, S.V. (1980): Numerical Heat transfer and fluid flow. Taylor and Francis Publishers, Rotterdam.

Pauwels, S.J. & T.A. Haines (1994): Survival, hatching, and emergence success of Atlantic salmon eggs planted in three Maine streams. North American Journal of Fisheries Management, 14: 125-130.

Peck, D.V., J.M. Lazorchak & D.J. Klemm (2000): Environmental monitoring and assessment program–surface water: Western pilot study field operations manual for wadeable streams. US Environmental protection Agency, Washington D.C.

Peterson, R.H. (1978): Physical characteristics of spawning Atlantic salmon gravel in some New Brunswick streams, Fisheries and Marine Service Technical Report 785, Fisheries and Environment St. Andrews, New Brunswick, Canada.

Peterson, N.P. & T.P. Quinn (1996): Spatial and temporal variation in dissolved oxygen in natural egg pockets of chum salmon, in Kennedy Creek, Washington. Journal of Fish Biology, 48: 131–143.

Petts, G.E. & A.M. Garnell (2005): Dams and geomorphology: Research progress and future directions. Geomorphology, 7(1–2): 27–47.

Philipps, J.D. (2010): Relative Importance Of Intrinsic, Extrinsic, And Anthropic Factors In The Geomorphic Zonation Of The Trinity River, Texas. Journal of the American Water Resource Association, 46(4): 807–823.

Piégay, H. & S.A. Schumm (2003): System approaches in Fluvial Geomorphology, in: Kondolf G.M. & H. Piégay: Tools in Fluvial Geomorphology. John Wiley & Sons Ltd, ISBN: 0–471–49142–X.

Pitlick, J. & P. Wilcock (2001): Relations Between Streamflow, Sediment–Transport and Aquatic Habitat in Regulated Rivers. Geomorphic Processes and Riverine Habitat, 4: 185–198.

Platts, W.S., Megahan, W.F. & W.G. Minshall (1983): Methods for Evaluating Stream, Riparian, and Biotic Conditions. USDA Forest Service, Rocky Mountain Research Station, Ogden, Utah.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. & J.C. Stromberg (1997): The natural flow regime: A paradigm for conservation and restoration of river ecosystems. BioScience 47: 769–784.

Poff, N.L. & J.V. Ward (1989): Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. Canadian Journal of Fisheries and Aquatic Sciences, 46: 1805–1818.

Poff, N.L. & J.V. Ward (1990): The physical habitat template of lotic systems: Recovery in the context of historical pattern of spatio–temporal heterogeneity. Environmental Management, 14: 629–646.

Poff, N.L., Allan, J.D., Palmer, M.A., Hart, D.D., Richter, B.D., Arthington, A.H., Rogers, K.H., Meyers, J.L. & J.A. Stanford (2003): River flows and water wars: emerging science for environmental decision making. Frontiers in Ecology and the Environment, 1: 298–306.

Poff, N.L. (2009): Managing for variation to sustain freshwater ecosystems. Journal of Water Resources Planning and Management, 2009, 135(1–4), (invited editorial).

Poff, N.L. & J.K.H. Zimmermann (2010): Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows, Freshwater Biology, 55: 194–205.

Poole, G.F. (2002): Fluvial landscape ecology: addressing uniqueness within the river discontinuum, Freshwater Biology, 47: 641–660.

Potyondy, J.P. & T.L. Sylte (2008): Discussion: "Assessment of methods for measuring embeddedness: application to sedimentation in flow regulated streams" by K.M. Sennatt, N.L. Salant, C.E. Renshaw, & F.J. Magilligan, Journal of the American Water Resources Association, 44 (1), 259–261.

Power, M.E., Tilman, D., Estes, J.A., Menge, B.A., Bond, W.J., Mills, L.S., Daily, G., Castilla, J.C., Lubchenco, J. & R.T. Paine (1996): Challenges in the quest for keystones. Bioscience, 46: 609–620.

Proffitt, G.T. & A.J. Sutherland (1983): Transport of nonuniform sediment. Journal of Hydraulic Research, IAHR, 21(1): 33–43.

Pulg, U. (2006): Kieslaichplaetze Entstehung, Degradierung, Restaurierung. Tagungsband zum Sachverstaendigenkuratorium (SVK)–Fischereitagung, Fulda.

Quinn, T.P. (2005): The Behavior and Ecology of Pacific Salmon and Trout. University of Washington Press, Seattle, WA: 328 pp.

Railsback, S.F., Harvey, B.C., Jackson, S.K. & R.H. Lamberson (2009): InSTREAM: the individual–based stream trout research and environmental assessment model. Albany, CA, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: p. 254.

Raleigh, R.F., Miller, W.J. & P.C. Nelson (1986): Habitat suitability index models and instream flow suitability curves: Chinook salmon, USFWS, Biological Report 82 (10.1222).

Raudkivi, A.J. (1982): Grundlagen des Sedimenttransports, Springer–Verlag, Berlin.

Revelli, R., Boano, F., Camporeale, C. & L. Ridolfi (2008): Intra–meander hyporheic flow in alluvial rivers. Water Resources Research, 44: W12428.

Reid, I. & J.B. Laronne (1995): Bedload sediment transport in an ephemeral stream and a comparison with seasonal and perennial counterparts. Water Resources Research, 31: 773–781.

Revenga, C., Brunner, J., Henninger, N., Kassem, K., & R. Payne (2000): Pilot Analysis of Global Ecosystems, Freshwater Systems. World Resources Institute, Washington, D.C.

Reynoldson, T.B., Norris, R.H., Resh, V.H., Day, K.E. & D.M. Rosenberg (1997): The reference condition: a comparison of multimetric and multivariate approaches to assess water–quality impairment using benthic macroinvertebrates. Journal of the North American Benthological Society 16: 833–852.

Ribberink, J.S. (1987): Mathematical modelling of one-dimensional morphological changes in rivers with non-uniform sediments, PhD-Thesis, Delft University of Technology, Netherlands.

Ribberink, J.S., Blom, A. & P. van der Sheer (2002): Multi–fraction techniques for sediment transport and morphological modeling in sand–gravel rivers', River Flow 2002, Bousmar and Zech (eds.):, Swets & Zeitinger, Lisse: 731–739.

Richardson, J.F. & W.N. Zaki (1954): Sedimentation and fluidisation, part I. Transactions of the Institution of Chemical Engineers, 32(1): 35–53.

Richards, K. (1982): Rivers: Form and Processes in Alluvial Channels. Methuen, London.

Richter, B.D., Baumgartner, J.V., Wigington, R. & D.P.Braun (1997): How much water does a river need? Freshwater Biology, 37: 231–249.

Robinson, C.T, Uehlinger, U. & M. Monaghan (2003): Effects of a multi–year experimental flood regime on macroinvertebrates downstream of a reservoir. Aquatic Sciences: Research Across Boundaries, 65: 210–222. DOI: 10.1007/s00027–003–0663–8.

Robinson, C.T. & U. Uehlinger (2008): Experimental floods cause ecosystem regime shift in a regulated river. Ecological Applications, 18: 511–526, DOI: 10.1890/07–0886.1.

Roche, P. (1994): Habitat availability and carrying capacity in the French part of the Rhine for Atlantic salmon (*Salmo salar*), Water Science Technology, 29, 257–265.

Rodi, W. (1980): Turbulence models and their application in hydraulics. A.A. Balkema, Rotterdam.

Rodi, W. (2006): DNS and LES of some engineering flows. Fluid Dynamics Research, 38: 145–173.

Rombough, P.J. (1988): Growth, aerobic metabolism and dissolved oxygen requirements of embryos and alevins of steelhead, Salmo gairdneri. Canadian Journal of Zoology, 66: 651–660.

Rosenfeld, J. (2003): Assessing the habitat requirements of stream fishes: An overview and evaluation of different approaches. Transactions of the American Fisheries Society, 132: 953–968.

Rosgen, D.L. (1996): Applied River Morphology. Wildland Hydrology, Pagosa Springs, Colorado.

Rouse, H. (1937): Modern conceptions of the mechanics of turbulence Transactions. ASCE, 102: 463–543.

Rubin, J.F. (1998): Survival and emergence pattern of sea trout fry in substrata of different compositions. Journal of Fish Biology, 53: 84–92.

Ruether, N. & N.R.B. Olsen (2005): Three dimensional modeling of sediment transport in a narrow 90° channel bend. Journal of Hydraulic Engineering, 131(10): 917–920.

Ruether, N. (2006): Computational fluid dynamics in fluvial sedimentation engineering. PhD–Thesis, Norwegian Institute of Technology, Trondheim.

Salski, A. (1992): Fuzzy knowledge–based models in ecological research. Ecological Modelling 63: 103–112.

Saltveit, S.J. (2006): The effects of stocking Atlantic salmon (*Salmo salar)*, in a Norwegian regulated river. Fisheries Management and Ecology, 13: 197–205.

Sanford, L.P. & J.P. Halka (1993): Assessing the paradigm of mutually exclusive erosion and deposition of mud, with examples from upper Chesapeake Bay. Marine Geology 114: 37–57.

Saueregger, G. (2008): Untersuchung von Kolmationsprozessen in der freien Fließstrecke der Lutz mittels eines physikalischen Modells. Diplomarbeit, Institut fuer Wasserbau und Wasserwirtschaft, Technische Universitaet Graz.

Saenger, N. & U.C.E. Zanke (2009): A depth–oriented view of hydraulic exchange patterns between surface water and the hyporheic zone, analysis of field experiments. Fundamental and Applied Limnology, 61: 9–27.

Schaelchli, U. (1992): The clogging of coarse gravel river beds by fine sediment. Hydrobiologia, 235: 189–197.

Schaelchli, U. (1993): Die Kolmation von Fliessgewaessersohlen: Prozesse und Berechnungsgrundlagen. PhD–Thesis Nr. 124, ETH Zuerich, Versuchsanstalt fuer Wasserbau, Hydrologie und Glaziologie.

Schaelchli, U. (1995): Basic Equation for siltration of riverbeds. Journal of Hydraulic Engineering, 121(3): 274–287.

Schaelchli, U. (2002): Innere Kolmation: Methoden zur Erkennung und Bewertung. Fischnetz–Publikation, Teilprojekt Eidgenoessische Anstalt fuer Wasserversorgung, Abwasserreinigung und Gewaesserschutz (EAWAG), Projekt 01/11.

Scheurer, T. & P. Molinari (2003): Experimental Floods in the River Spoel, Swiss National Park: Framework, Objectives and Design. Aquatic Sciences, Research Across Boundaries, 65: 183–190, DOI: 10.1007/s00027-003-0667-4.

Scheurer, K., Alewell, C., Baenninger, D. & P. Burkhardt–Holm (2009): Climate and land–use changes affecting river sediment and brown trout in alpine countries, a review. Environmental Scientific Pollution Research, 16: 232–242.

Schiemer, F. (2000): Fish as indicators for the assessment of the ecological integrity of large rivers. Hydrobiologia, 422/423: 271–278.

Schiemer, F., Keckeis, H. & E. Kamler (2003): The early life history stages of riverine fish: ecophysiological and environmental bottlenecks. Comparative Biochemistry and Physiology, Part A, 133: 439–449.

Schiff, R., MacBroom, J. & J. Armstrong–Bonin (2006): River Restoration and Fluvial Geomorphology White Paper, R-WD-06-27, New Hampshire.

Schlichting, H. (1979): Boundary layer Theory. McGraw–Hill Book Company, New York.

Schmutz, S., Melcher, A., Holzer, G. & G. Hollerer (1999): Arbeitspaket 19a: Habitatmodellierung Lebensraumansprueche der Leitfischarten Nase, Barbe, Huchen und AEsche. Amt der NOE Landesregierung, Bundeswassebauverwaltung Traisenwasserverband, Wien.

Schmutz, S., Kaufmann, M., Vogel, B., Jungwirth, M. & S. Muhar (2000): A multi–level concept for fish–based, river–type–specific assessment of ecological integrity. Hydrobiologia, 422: 279–289.

Schneider, M. (2001): Habitat– und Abflussmodellierung fuer Fließgewaesser mit unscharfen Berech–nungsansaetzen. – Dissertation, Mitteilungen des Instituts fuer Wasserbau, Heft 108, Universitaet Stuttgart, Eigenverlag, Institut fuer Wasserbau der Universitaet Stuttgart, Stuttgart.

Schneider, M., Kopecki, I., Eisner, A. & M. Noack (2007): Linking morphodynamic and fish habitat modeling – Case Study Bodendorf, River Mur (Austria). 32th IAHR Congress, Venice, Italy.

Schuett–Hames, D. & A. Pleus (1996): Literature Review & Monitoring Recommendations for Salmonid Spawning Habitat Availability, Northwest Indian Fisheries Commission: 25 pp.

Schuett–Hames, D., Conrad, R., Pleus, A. & K. Lautz (1996): Salmonid spawning gravel scour: a literature review with recommendations for a watershed analysis monitoring methodology, Northwest Indian Fisheries Commission: 22 pp.

Schumm, S.A., (2005): River Variability and Complexity. Cambridge University Press, New York.

Schwarz, M., Fuchs, S. & H.H. Hahn (2003): Mikrobielle Kolmation und Dekolmation in Bodenfiltern. Wasser und Abfall, 10/2003: 20–23.

Schwoeberl, J. (1961): UEber die Lebensbedingungen und die Besiedlung des hyporheischen Lebesraumes. Archiv fuer Hydrobiologie, 25: 182–214.

Scrivener, J.C. (1988): Two devices to assess incubation survival and emergence of salmonid fry in an estuary streambed. North American Journal of Fisheries Management 8: 248–258.

Sear, D.A., Frostick, L.B., Rollinson, G. & T.E. Lisle (2008): The significance and mechanics of fine–sediment infiltration and accumulation in gravel spawning beds, in: Sear, David A. and DeVries, Paul (eds.): Salmonid Spawning Habitat in Rivers: Physical Controls, Biological Responses, and Approaches to Remediation. Bethesda, USA, American Fisheries Society: 149–174. (Symposium 65).

Sedgewick, S.D. (1982): The Salmon Handbook: The Life And Cultivation Of Fishes Of The Salmon Family. London, Andre Deutch Ltd.

Sennatt, K.M., Salant, N.L., Renshaw, C.E. & F.J. Magilligan (2006): Assessment of methods for measuring embeddedness: application to sedimentation in flow regulated streams. Journal of American Water Resources Association, 42: 1671–1681.

Seydell, I., Ibisch, R.B. & U.C.E. Zanke (2009): Intrusion of suspended sediments into gravel riverbeds: influence of bed topography studied by means of field and laboratory experiments. Fundamental And Applied Limnology, Advances in Limnology, 61: 67–85.

Shields, A. (1936): Anwendung der AEhnlichkeitsmechanik und der Turbulenz Forschung auf die Geschiebebewegung. Mitteilungen der Preußischen Versuchsanstalt fuer Wasserbau und Schiffbau, Berlin, Germany.

Shirvell, C.S. & R.G. Dungey (1983): Microhabitats chosen by brown trout for feeding and spawning in rivers. Transactions of the American Fisheries Society 112: 355–367.

Sidle, R.C. & Y. Onda (2004): Hydrogeomorphology: overview of an emerging science. Hydrological Processes, 18: 597–602.

Sloff, K. & E. Mosselman (2007): Implications of Bed–Schematization in Morphological Models with Graded Sediments. Fall Meeting 2007, American Geophyiscal Union.

Smiarowski, A. (2010): The Evaluation of a Two–Dimensional Sediment Transport and Bed Morphology Model Based on the Seymour River. Master Thesis, University of British Columbia, Vancouver.

Smith, J.D. & S.R. McLean (1977): Spatially averaged flow over a wavy surface, Journal of Geophysical Research, 82: 1735–1746.

Smith, L.W. (2002): A Framework of Ecosystem Processes for Evaluating Effects of Dams on Endangered Species. Northwest Science, 76(4): 361–366.

Souchon Y. & H. Capra (2004): Aquatic habitat modelling: biological validations of IFIM/Phabsim methodology and new perspectives. Hydroécologie Appliqueé 14: 9–25.

Soulsby, C., Youngson, A.F., Moir, H.J. & I.A. Malcom (2001): Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: a preliminary assessment. The Science of the Total Environment, 265(1–3): 295–307.

Sowden T.K. & G. Power (1985): Prediction of rainbow trout embryo survival in relation to groundwater seepage and particle size of spawning substrates, Transactions of the American Fisheries Society 114: 804-812.

Spasojevic, M. & F.M. Holly (2008): Two– and three–dimensional numerical simulation of mobile–bed hydrodynamics and sedimentation, in: H.G. Marcelo (eds.): Sedimentation engineering: processes, measurements, modeling, and practice. American Society of Civil Engineers: 683–761.

Staes, J., Backx, H. & P. Meire (2008): Integrated Water Management: 263–301, in: Moerlins, J.E., Khankhasayev, M.K., Leitman, S.F. & E.J. Makhumdov (eds.): Transboundary Water Recourses: A Foundation for Regional Stability in Central Asia. Springer Netherlands, ISBN: 978–1–4020–6736–5.

Stalnaker, C.B., Lamb, B.L., Henriksen, J., Bovee, K. & J. Bartholow (1995): The Instream Flow Incremental Methodology: A Primer for IFIM. Washington DC, U.S. Geological Survey Biological Report 29: p. 45.

Stanford, J.A. & J.V. Ward (1993): An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor. Journal of North American Benthologic Society, 12: 48–60.

Stanley, E.H., Powers, S.M. & N.R. Lottig (2010): The evolving legacy of disturbance in stream ecology: concepts, contributions, and coming challenges, Journal of North American Benthologic Society, 29(1): 67-83

Sternecker, K. & J. Geist (2010): The effects of stream substratum composition on the emergence of salmonid fry. Ecology of Freshwater Fish, 19(4): 537–544.

Stocker, Z.S.J. & D.D. Williams (1972): A freezing core method for describing the vertical distribution of sediments in a streambed. Limnology and Oceanography, 17: 136–138.

Stonedahl, S.H., Harvey, J.W., Woerman, A., Salehin, M. & A.I. Packman (2010): A Multiscale Model for Integrating Hyporheic Exchange from Ripples to Meanders. Water Resources Research, 46: W12539,

Storey, R.G., Fulthorpe, R.R. & D.D. Williams (1999): Perspectives and predictions on the microbial ecology of the hyporheic zone. Freshwater Biology, 41: 119–30.

Sullivan, S.M.P., Watzin, M.C. & W.C. Hession (2006): Influence of stream geomorphic condition on fish communities in Vermont, USA. Freshwater Biology, 51(10): 1811–1826.

Sylte, T. & C. Fischenich (2002): Techniques for Measuring Substrate Embeddedness. ERDC: TN–EMRRP–SP–36.

Syvitrski, J.P.M., Voeroesmarty, C.J., Kettner, A.J. & P. Green (2005): Impact of Humans on the Flux of Terrestrial Sediment to the Global Ocean, Science, 308: 376-380.

Tagart, J.V. (1976): The survival from egg deposition to emergence of coho salmon in the Clearwater River, Jefferson County, Washington. Master thesis, University of Washington, Seattle.

Tappel, P.D. & T.C. Bjornn (1983): A new method of relating size of spawning gravel to salmonid embryo survival. North American Journal of Fisheries Management 3: 123–135.

Teakle, I. & P. Nielsen (2003): Two–phase modelling of vertical sediment fluxes in oscillatory sheet flow. Coastal sediments '03, Florida, USA.

Terzaghi, K. & R.B. Peck (1964): Soil Mechanics in Engineering Practice. Wiley, New York.

Tetzlaff, D., Soulsby, C., Youngson, A.F., Gibbins, C.N., Bacon, P.J., Malcolm, I.A. & S.J. Langan (2005): Variability in stream flow and temperatures during ecologically sensitive time periods: a preliminary assessment of the implications for Atlantic salmon. Hydrology and Earth System Sciences: 691–729.

Thoms, M.C. & M.E. Parsons (2002): Ecogemorphology: an interdisciplinary approach to river science. International Association of Hydrological Sciences, 227: 113–119.

Thorp, J.H., Flotemersch, J.E., Delong, M.D., Casper, A.F., Thoms, M.C., Ballantyne, F., Williams, B.S., O'neill, B.J. & C.S. Haase (2010): Linking Ecosystem Services, Rehabilitation, and River Hydrogeomorphology. BioScience 60: 67–74.

Toffaleti, F.B. (1968): A procedure for computation of the total river sand discharge and detailed distribution, bed to surface. Technical Report No.: 5, US Army Corps of Engineers, Vicksburg, Mississippi, USA.

Tonina, D. (2005): Interaction between river morphology and intra–gravel flow paths within the hyporheic zone, PhD–Thesis. University of Idaho: 129 pp.

Tonina, D. & J.M. Buffingtion (2009): Hyporheic Exchange in Mountain Rivers I: Mechanics and Environmental Effects, Geography Compass 3/3: 1063–1086.

Truempy, R., Schmid, S.M.,Conti, P. & N. Froitzheim (1997): Erlaeuterungen zur Geologischen Karte des Schweizerischen Nationalparks (Spezialkarte Nr.122), Nationalpark-Forschung in der Schweiz, 1-40.

Uehlinger, U. & M.W. Naegeli (1998): Ecosystem metabolism, disturbance, and stability in a prealpine gravel bed river, Journal of North Ameriam Benthological Society, 17: 165-178.

Uehlinger, U., Kawecka, B. & C.T. Robinson (2003): Effects of experimental floods on periphyton and stream metabolism below a high dam in the Swiss Alps (River Spoel). Aquatic Sciences: Research Across Boundaries, 65: 199–209.

U.S. Environmental Protection Agency (EPA) (1986): Ambient water quality criteria for dissolved oxygen, EPA, 440/5-86-003, Criteria and Standards Division, Washington DC.

Vadas, R.L., & D.J. Orth (2001): Formulation of habitat suitability models for stream–fish guilds: do the standard methods work? Transactions of the American Fisheries Society, 130: 217–235.

Van Broekhoven, E., Adriaenssens, V., De Baets, B. & P.F.M. Verdonschot (2006): Fuzzy rule–based macroinvertebrate habitat suitability models for running waters. Ecological Modelling, 198: 71–84.

Van Rijn, L.C. (1984): Sediment transport, part II: suspended load transport. Journal of Hydraulic Engineering, ASCE, 110(11): 1613–1641.

Van Rijn, L.C. (1993): Principles of sediment transport in rivers, estuaries and coastal seas. Aqua Publications, Amsterdam, the Netherlands.

Varley, M.E. (1967): British Freshwater Fishes – Factors Affecting their Distribution, London, Fishing News (Books) Limited.

Vaughan, I.P. & S.J. Ormerod (2010): Linking ecological and hydromorphological data: approaches, challenges and future prospects for riverine science. Aquatic Conservation: Marine and Freshwater Ecosystems, 20(S1): 125–130.

Vaux, W.G. (1968): Intragravel flow and interchange of water in a streambed. Fishery Bulletin, 66, 479–489.

Velsen, F.P.J. (1980): Embryonic development in eggs of sockeye salmon (*Oncorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences, 49: 19.

Vollmer, S. (2005): Einfluss der Oberflaechenstroemung auf die permeable Gewaessersohle. Mitteilungen des Instituts fuer Wasserwirtschaft und Kulturtechnik, 231, Universitaet Karlsruhe.

Walters, D.M., Roy, A.J. & D.S. Leigh (2009): Environmental indicators of macroinvertebrate and fish assemblage integrity in urbanizing watersheds. Ecological Indices, 9(6): 1222–1233.

Wentworth, C.K. (1922): A scale of grade and class terms for clastic sediments, The Journal of Geology, 30: 377-392

Wheaton, J.M., Brasington, J., Darby, S., Merz, J., Pasternack, G.B., Sear, D. & D. Vericat (2010): Linking geomorphic changes to salmonid habitat at a scale relevant to fish. River Research and Applications, 26: 469–486, DOI: 10.1002/rra.1305.

White, D.S. (1993): Perspectives on defining and delineating hyporheic zones. Journal of the North American Benthological Society, 12: 61–69.

Wickett, W.P. (1954): The oxygen supply to salmon eggs in spawning beds. Journal of the Fisheries Research Board of Canada 11: 933-953.

Wieprecht, S., Eisner, A. & M. Noack (2006): Modeling Approach to Simulate Habitat Dynamics. River Flow 2006, Proceedings of the International Conference on Fluvial Hydraulics, Lisbon, Volume 2: 2055–2063.

Wieprecht, S., Eisner, A. & M. Noack (2007): Development of Ecological Oriented Flow Regimes based on Habitat, 6th International Symposium on Ecohydraulics, Christchurch, New Zealand.

Wieprecht, S. (2009): Morphologie als Indikator fuer die Habitatqualitaet, 12. Gewaessermorphologisches Kolloquium, ISBN: 1866-220X, Federal Institute of Hydrology, Koblenz, Germany

Wilson, M.A. & R. Howarth (2002): Discourse–based valuation of ecosystem services: establishing fair outcomes through group deliberation. Ecological Economics 41: 431–443.

Witzel, L.D. & H.R: MacCrimmon (1981): Role of gravel substrate on ova survival and alevin emergence of rainbow trout, Canadian Journal of Zoology 59: 629-636.

Wolfert, H.P. (2001): Geomorphological Change and River Rehabillitation, Case Studies of Lowland Fluvial Systems in the Netherlands. Alterra Scientific Contribution 6, PhD–Thesis, University of Utrecht.

Wohl, E., Cooper, D., Poff, N.L., Rahel, F., Staley, D. & D. Winters (2007): Assessment of stream ecosystem function and sensitivity in the Bighorn National Forest, Wyoming. Environmental Management, 40: 284–302.

Wollbaek, J., Thue, R. & J. Heggenes (2008): Redd site microhabitat utilization and quantative models for wild large brown trout in three contrasting boreal rivers, North American Journal of Fisheries Management 28: 1249-1258.

Wondzell, S.M. & F.J. Swanson (1999): Floods, channel change and the hyporheic zone. Water Resoures Research, 35: 555–567.

Wooster, J.K., Riebe, C.S. & F.K. Ligon (2008): Quantifying upper particle size limits of salmonid spawning gravel: analysis of fall run Chinook salmon of the Sacramento River, Poster Presentation at the American Geophysical Union, Fall Meeting, San Francisco, California.

Wooster, J.K., Dusterhoff, S.R., Cui, Y., Sklar, L.S., Dietrich, W.E. & M. Malko (2008): Sediment supply and relative size distribution effects on fine sediment infiltration into immobile gravels. Water Resources Research, 44: W03424.

Worman, A., Packman, A.I., Johansson, H. & K. Jonsson (2002): Effect of flowinduced exchange in hyporheic zones on longitudinal transport of solutes in streams and rivers. Water Resources Research 38(1): 15–29.

Wu, F. (2000): Modelling embryo survival affected by sediment deposition into salmonid spawning gravels: application to flushing flow principles. Water Resources Research, 36(6): 1595–1603.

Wu, J. & J. L. David (2002): A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications. Ecological Modelling, 153: 7–26.

Wu, W. & S.S.Y. Wang (1999): Movable bed roughness in alluvial rivers. Journal of Hydraulic Engineering, ASCE, 125(12): 1309–1312.

Wu, W. & D.A. Vieira (2002): One–dimensional channel network model CCHE1D 3.0. Technical manual, Technical Report No.: NCCHE–TR–2002–1, National Center for Computational Hydroscience and Engineering, University of Mississippi, USA.

Wu, W., Wang, S.S.Y & Y. Jia (2000): Nonuniform sediment transport in alluvial rivers, Journal of Hydraulic Research, IAHR, 38(6): 427–434.

Wu, W. & S.S.Y. Wang (2006): Formulas for sediment porosity and settling velocity. Journal of Hydraulic Engineering, ASCE, 132(8): 858–862.

Wu, W. (2007): Computational River Dynamics. Taylor & Francis e–Library, ISBN: 978–0–415–44961–8 (hardcover).

Yalin, M.S. (1972): Mechanics of Sediment Transport. Pergamon Press.

Yalin, M.S. (1977): Mechanics of Sediment Transport. Pergamon, Oxford, United Kingdom.

Yalin, M.S. & E. Karahan (1979): Inception of sediment transport. Journal of Hydraulic Divisons., ASCE, 105(11): 1433–1443.

Yang, C.T. (1973): Incipient motion and sediment transport. Journal of. Hydaulic Divisons., ASCE, 99(HY10): 1679–1704.

Yang, C.T. (1984): Unit stream power equation for gravel. Journal of Hydraulic Engineering, ASCE, 110(12).

Yang, C.T. (2006): Erosion and Sedimentation Manual. Reclamation: Managing Water in the West, U.S. Department of the Interior Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Colorado.

Yang, S.Q. & S.Y. Lim (2003): Total Load Transport Formula for Flow in Alluvial Channels. Journal of Hydraulic Engineering ASCE, 129(1): 68−72.

Yitian, L., Zang, W., Yong, H. and W. Daxi (2007): Water–sediment regimes and river health. Environmental Informatics Archives, 5: 312–320.

Young, T.F. & S. Sanzone (2002): A framework for assessing and reporting on ecological condition, Prepared by the Ecological Reporting Panel, Ecological Processes and Effects Committee. EPA Science Advisory Board, Washington, DC: 142.

Zadeh, L.A. (1965): Fuzzy Sets. Information and Control, 8: 338–353.

Zanke, U. (1990): Der Beginn der Sedimentbewegung als Wahrscheinlichkeitsproblem. Wasser & Boden, Heft 1.

Zanke, U. (2002): Hydromechanics of Rivers and Coastal Waters. Pary/Blackwell, Berlin.

Zhang, R.J. (1961) River Dynamics. Industry Press, Beijing, China.

Zimmer, M.P. & M. Power (2006): Brown trout spawning habitat selection preferences and redd characteristics in the Credit River, Ontario. Journal of Fish Biology, 68: 1333–1346.

Zimmermann, A.E. & M. Lapointe (2005): Intergranular flow velocity through salmonid redds: sensitivity to fines infiltration from low intensity sediment transport events. River Research and Applications, 21(8): 865–881.

Zyserman, J.A. & J. Fredsøe (1994): Data analysis of bed concentration of suspended sediment. Journal of Hydraulic Engineering, ASCE, 120(9): 1021–1042.

Appendix

Appendix 1 – the numerical model SSIIM2

Appendix 1.1: Exemplary control-file in SSIIM2 to calculate sediment infiltration in the laboratory flume.

```
F 1 D                      debugging options
F 2 UORS                   automatic execution possibility
F 6 0.015 1.5 0.3          Coefficients for van Rijn formula (suspend load)
F 11 2.65 -0.047           sediment density, critical shear stress
F 16 0.078                 roughness
F 33 20.0 100              time step, number of inner iterations
F 36 2                     free water surface
F 37 3                     sediment computation
F 48 7                     2D-Tecplot-File
F 60 1 0                   Hunter-Rouse distribution
F 64 13                    grid generation algorithm
F 84 0                     only suspended load
F 87 0.6                   vertical distribution of cells
F 94 0.001 0.01            wetting & drying
F 102 1                    change the shape of a cell at boundary for wetting drying
F 104 1                    prevent crashes for single cells
F 105 5                    water level update after n iteration
F 106 0.106                thickness of active layer
F 112 1                    use koordina for initial water level
F 113 7                    stabilization algorithm in shallow regions
F 134 2                    number of sediment layers
F 168 10                   multgrid solver
F 169 4 -0.60              hiding/exposure
F 206 2                    number of processors
F 235 10                   stabilization algorithm for triangular cells

P 10 360                   output interval Tecpot

G 1 84 14 11 6             number of cells in each direction, number of particles
G 3 0 10 20 30 40 50 60 70 80 90 100    vertical distribution of cells
G 6 3600 0 2 0.01 0.01     data for calculating water level with adaptive grid
G 24 3 u 7 0 w 1 0 N 1 2   specification of output parameters

S 1 0.078 1.1729           particle size and settling velocity
S 2 0.033 0.7626           particle size and settling velocity
S 3 0.023 0.6364           particle size and settling velocity
S 4 0.0053 0.3032          particle size and settling velocity
S 5 0.0004 0.0561          particle size and settling velocity
S 6 0.00001 0.0001         particle size and settling velocity

K 1 6000 50000             number of outer iterations
K 2 0 1                    use of wall laws
K 3 0.8 0.8 0.8 0.2 0.5 0.5      relaxation factors
K 4 1 1 1 5 1 1            number of iteration for each equation
K 5 0 0 0 10 0 0           block correction
K 6 1 1 1 0 0 0            numerical calculation scheme
```

Appendix 2 – Applied fuzzy-sets and fuzzy-rules in the modelling framework

Appendix 2.1: Fuzzy-rule-system to compute the interstitial habitat suitabilities (IHS) during the incubation period (IHS_{egg}, IHS_{hatch}, IHS_{larv}). The corresponding fuzzy-sets are visualized in Chapter C.1.3.

ID	Perm	Temp	Resp	IHS egg	IHS hatch	IHS larvae
1	VL	VL	L	L	L	L
2	VL	VL	M	L	L	L
3	VL	VL	H	L	L	L
4	VL	L	L	L	L	L
5	VL	L	M	L	L	L
6	VL	L	H	L	L	L
7	VL	M	L	L	L	L
8	VL	M	M	L	L	L
9	VL	M	H	L	L	L
10	VL	H	L	L	L	L
11	VL	H	M	L	L	L
12	VL	H	H	L	L	L
13	VL	VH	L	L	L	L
14	VL	VH	M	L	L	L
15	VL	VH	H	L	L	L
16	L	VL	L	L	L	L
17	L	VL	M	L	L	L
18	L	VL	H	L	L	L
19	L	L	L	M	L	M
20	L	L	M	L	L	L
21	L	L	H	L	L	L
22	L	M	L	VH	M	H
23	L	M	M	H	L	M
24	L	M	H	L	L	L
25	L	H	L	M	L	M
26	L	H	M	L	L	L
27	L	H	H	L	L	L
28	L	VH	L	L	L	L
29	L	VH	M	L	L	L
30	L	VH	H	L	L	L
31	M	VL	L	L	L	L
32	M	VL	M	L	L	L
33	M	VL	H	L	L	L
34	M	L	L	VH	M	H
35	M	L	M	H	L	M
36	M	L	H	L	L	L
37	M	M	L	VH	H	H
38	M	M	M	VH	M	H
39	M	M	H	M	L	L
40	M	H	L	VH	M	H
41	M	H	M	H	L	M
42	M	H	H	L	L	L
43	M	VH	L	L	L	L
44	M	VH	M	L	L	L
45	M	VH	H	L	L	L
46	H	VL	L	L	L	L
47	H	VL	M	L	L	L
48	H	VL	H	L	L	L
49	H	L	L	VH	M	H
50	H	L	M	H	L	M
51	H	L	H	L	L	L
52	H	M	L	VH	VH	VH
53	H	M	M	VH	H	VH
54	H	M	H	M	L	M
55	H	H	L	VH	M	H
56	H	H	M	H	L	M
57	H	H	H	L	L	L
58	H	VH	L	L	L	L
59	H	VH	M	L	L	L
60	H	VH	H	L	L	L
61	VH	VL	L	L	L	L
62	VH	VL	M	L	L	L
63	VH	VL	H	L	L	L
64	VH	L	L	VH	M	H
65	VH	L	M	H	L	M
66	VH	L	H	L	L	L
67	VH	M	L	VH	VH	VH
68	VH	M	M	VH	H	VH
69	VH	M	H	M	L	M
70	VH	H	L	VH	M	H
71	VH	H	M	H	M	M
72	VH	H	H	L	L	L
73	VH	VH	L	L	L	L
74	VH	VH	M	L	L	L

Perm = permeability [cm/h]
Temp=temperature [°C]
Resp = hyporheic respiration [gO_2/m^2d]
IHS = interstitial habitat suitability [-]
VL = very low
L = low
M = medium
H = high
VH = very high

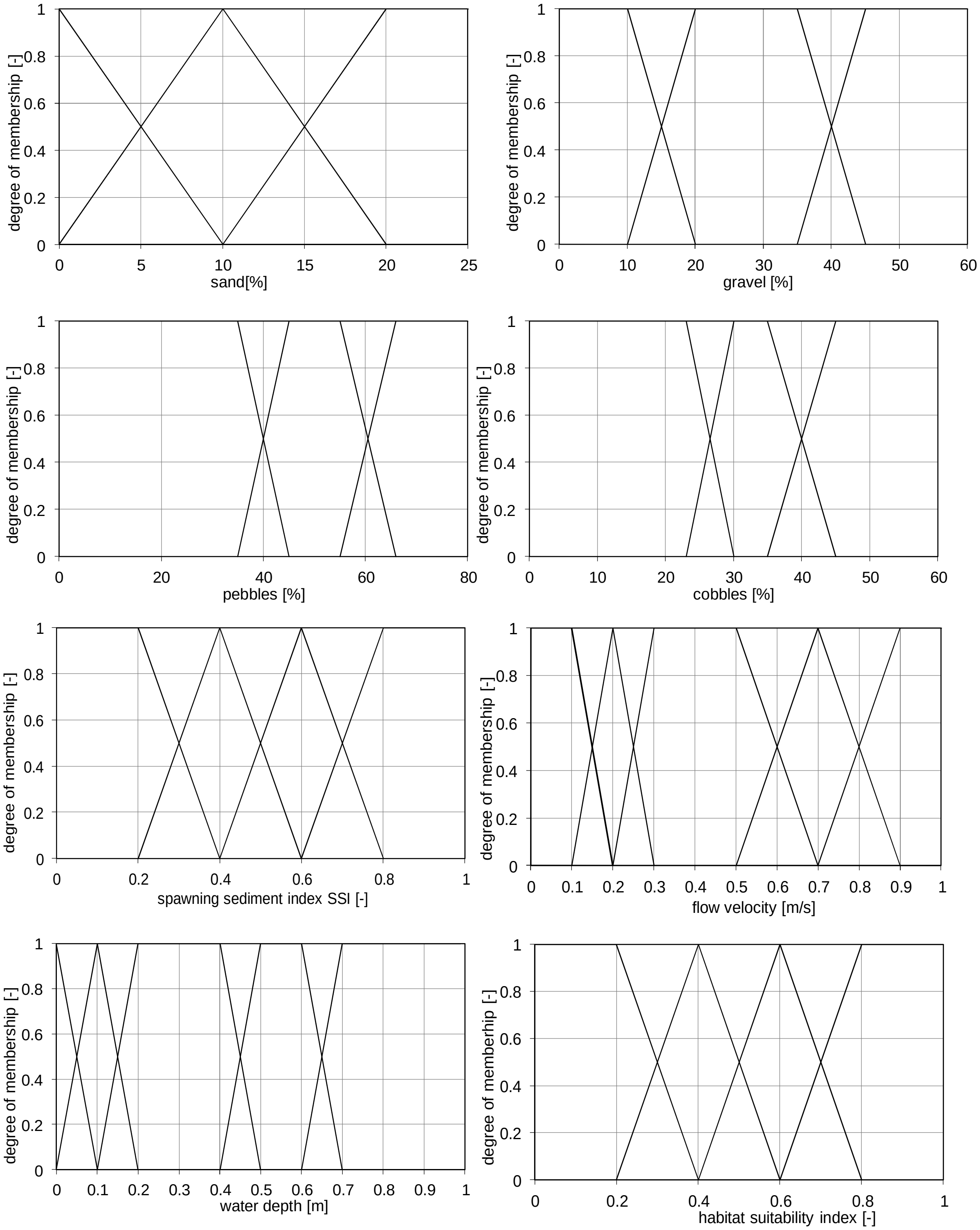
Appendix 2.2: Habitat requirements of brown trout on the habitat variable flow velocity (based on literature reviews from Armstrong et al. (2003), Louhi et al. (2008) and Jonsson & Jonsson (2011).

flow velocity [m/s]	data type	reference
0.20-0.55	range	Louhi et al. (2008)
0.15-0.75	range	Shirwell & Dungey (1983)
0.11-0.80	range	Witzel & MacCrimmon (1983)
0.15-0.80	range	Jonsson & Jonsson (2011)
0.23-0.50	range	Zimmer & Power (2006)
0.39	mean	Shirwell & Dungey (1983)
0.47	mean	Wollebaek et al. (2008)
0.48	mean	Witzel & MacCrimmon (1983)

Appendix 2.3: Habitat requirements of brown trout on the habitat variable water depth (based on literature reviews from Armstrong et al. (2003), Louhi et al. (2008) and Jonsson & Jonsson (2011).

water depth [m]	data type	reference
0.15-0.45	range	Louhi et al. (2008)
0.23-2.15	range	Wollebaek et al. (2008)
0.20-0.49	range	Heggberget et al. (1998)
0.06-0.82	range	Jonsson & Jonsson (2011)
0.27-0.52	range	Zimmer & Power (2006)
0.32	mean	Shirwell & Dungey (1983)
1.03	mean	Wollbaek et al. (2008)
0.26	mean	Witzel & MacCrimmon (1983)

Appendix.2.4: Fuzzy-sets to compute the spawning sediment index (SSI) and the habitat suitability index for the spawning stage (HSI_{spawn}) of brown trout in the River Spoel.



Appendix.2.5: Fuzzy-rule system to compute the spawning sediment index (SSI) of brown trout.

ID	%S	%G	%P	%C	SSI
1	L	L	L	L	L
2	L	L	L	M	L
3	L	L	L	H	L
4	L	L	M	L	L
5	L	L	M	M	L
6	L	L	M	H	L
7	L	L	H	L	L
8	L	L	H	M	L
9	L	L	H	H	L
10	L	M	L	L	L
11	L	M	L	M	L
12	L	M	L	H	L
13	L	M	M	L	VH
14	L	M	M	M	M
15	L	M	M	H	L
16	L	M	H	L	H
17	L	M	H	M	M
18	L	M	H	H	L
19	L	H	L	L	L
20	L	H	L	M	L
21	L	H	L	H	L
22	L	H	M	L	H
23	L	H	M	M	M
24	L	H	M	H	L
25	L	H	H	L	M
26	L	H	H	M	L
27	L	H	H	H	L
28	M	L	L	L	L
29	M	L	L	M	L
30	M	L	L	H	L
31	M	L	M	L	M
32	M	L	M	M	L
33	M	L	M	H	L
34	M	L	H	L	L
35	M	L	H	M	L
36	M	L	H	H	L
37	M	M	L	L	L
38	M	M	L	M	L
39	M	M	L	H	L
40	M	M	M	L	VH
41	M	M	M	M	M
42	M	M	M	H	L
43	M	M	H	L	H
44	M	M	H	M	M
45	M	M	H	H	L
46	M	H	L	L	L
47	M	H	L	M	L
48	M	H	L	H	L
49	M	H	M	L	M
50	M	H	M	M	M
51	M	H	M	H	L
52	M	H	H	L	L
53	M	H	H	M	L
54	M	H	H	H	L
55	H	L	L	L	L
56	H	L	L	M	L
57	H	L	L	H	L
58	H	L	M	L	L
59	H	L	M	M	L
60	H	L	M	H	L
61	H	L	H	L	L
62	H	L	H	M	L
63	H	L	H	H	L
64	H	M	L	L	L
65	H	M	L	M	L
66	H	M	L	H	L
67	H	M	M	L	L
68	H	M	M	M	L
69	H	M	M	H	L
70	H	M	H	L	L
71	H	M	H	M	L
72	H	M	H	H	L
73	H	H	L	L	L
74	H	H	L	M	L
75	H	H	L	H	L
76	H	H	M	L	L
77	H	H	M	M	L
78	H	H	M	H	L
79	H	H	H	L	L
80	H	H	H	M	L
81	H	H	H	H	L

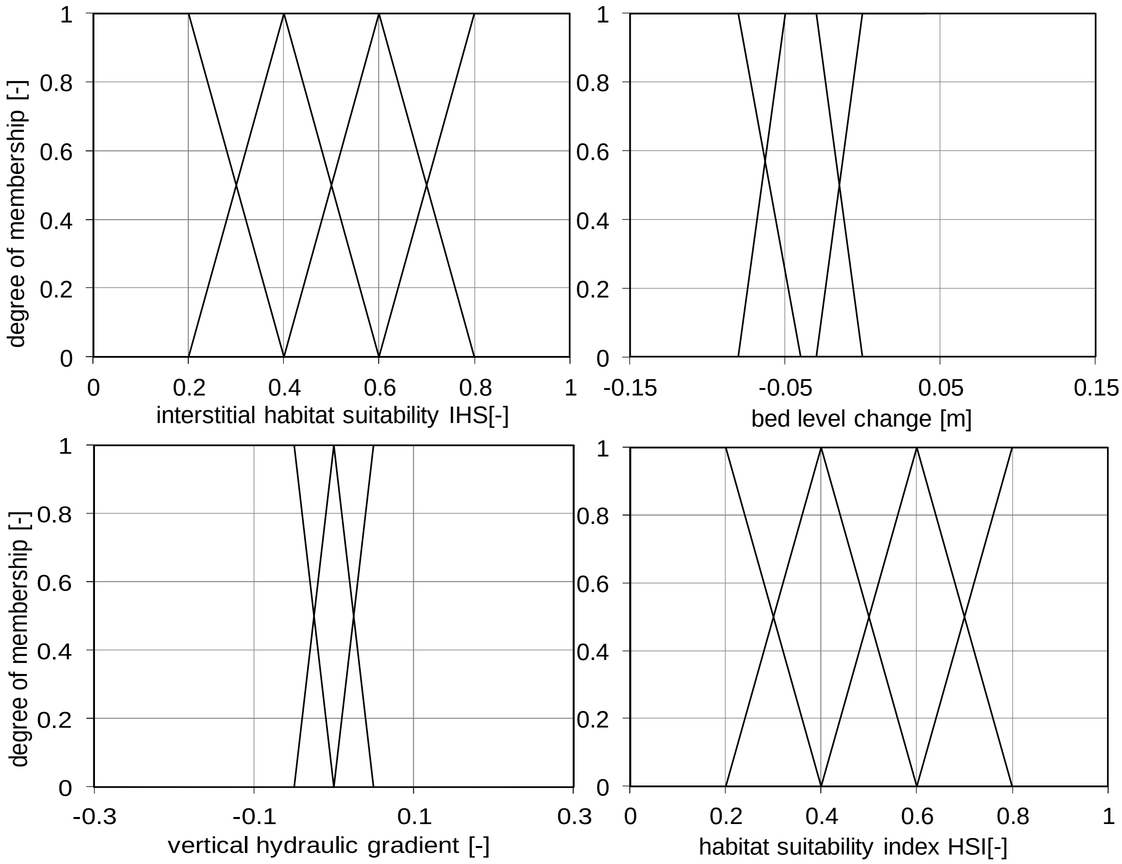
%S = percentage of sediment class sand
%G = percentage of sediment class gravel
%S = percentage of sediment class pebbles
%S = percentage of sediment class cobbles
SSI = sediment suitability index
VL = very low
L = low
M = medium
H = high
VH = very high

Appendix 2.6: Fuzzy-rule system to compute the habitat suitability index (HSI_{spawn}) of spawning (brown trout).

ID	vel	dep	SSI	HSI
1	VL	VL	L	L
2	VL	VL	M	L
3	VL	VL	H	L
4	VL	VL	VH	L
5	VL	L	L	L
6	VL	L	M	L
7	VL	L	H	L
8	VL	L	VH	L
9	VL	M	L	L
10	VL	M	M	L
11	VL	M	H	L
12	VL	M	VH	L
13	VL	H	L	L
14	VL	H	M	L
15	VL	H	H	L
16	VL	H	VH	L
17	VL	VH	L	L
18	VL	VH	M	L
19	VL	VH	H	L
20	VL	VH	VH	L
21	L	VL	L	L
22	L	VL	M	L
23	L	VL	H	L
24	L	VL	VH	L
25	L	L	L	L
26	L	L	M	M
27	L	L	H	M
28	L	L	VH	M
29	L	M	L	L
30	L	M	M	M
31	L	M	H	M
32	L	M	VH	M
33	L	H	L	L
34	L	H	M	M
35	L	H	H	M
36	L	H	VH	M
37	L	VH	L	L
38	L	VH	M	L
39	L	VH	H	L
40	L	VH	VH	L
41	M	VL	L	L
42	M	VL	M	L
43	M	VL	H	L
44	M	VL	VH	L
45	M	L	L	L
46	M	L	M	M
47	M	L	H	H
48	M	L	VH	VH
49	M	M	L	L
50	M	M	M	M

ID	vel	dep	SSI	HSI
51	M	M	H	H
52	M	M	VH	VH
53	M	H	L	L
54	M	H	M	M
55	M	H	H	H
56	M	H	VH	VH
57	M	VH	L	L
58	M	VH	M	L
59	M	VH	H	L
60	M	VH	VH	L
61	H	VL	L	L
62	H	VL	M	L
63	H	VL	H	L
64	H	VL	VH	L
65	H	L	L	L
66	H	L	M	M
67	H	L	H	H
68	H	L	VH	VH
69	H	M	L	L
70	H	M	M	M
71	H	M	H	H
72	H	M	VH	VH
73	H	H	L	L
74	H	H	M	M
75	H	H	H	M
76	H	H	VH	H
77	H	VH	L	L
78	H	VH	M	L
79	H	VH	H	L
80	H	VH	VH	L
81	VH	VL	L	L
82	VH	VL	M	L
83	VH	VL	H	L
84	VH	VL	VH	L
85	VH	L	L	L
86	VH	L	M	L
87	VH	L	H	L
88	VH	L	VH	L
89	VH	M	L	L
90	VH	M	M	L
91	VH	M	H	L
92	VH	M	VH	L
93	VH	H	L	L
94	VH	H	M	L
95	VH	H	H	L
96	VH	H	VH	L
97	VH	VH	L	L
98	VH	VH	M	L
99	VH	VH	H	L
100	VH	VH	VH	L

Appendix 2.7: Fuzzy-sets and fuzzy-rule-system to compute the habitat suitability index during the incubation period (HSI_{egg}, HSI_{hatch}, HSI_{larv}) of brown trout.

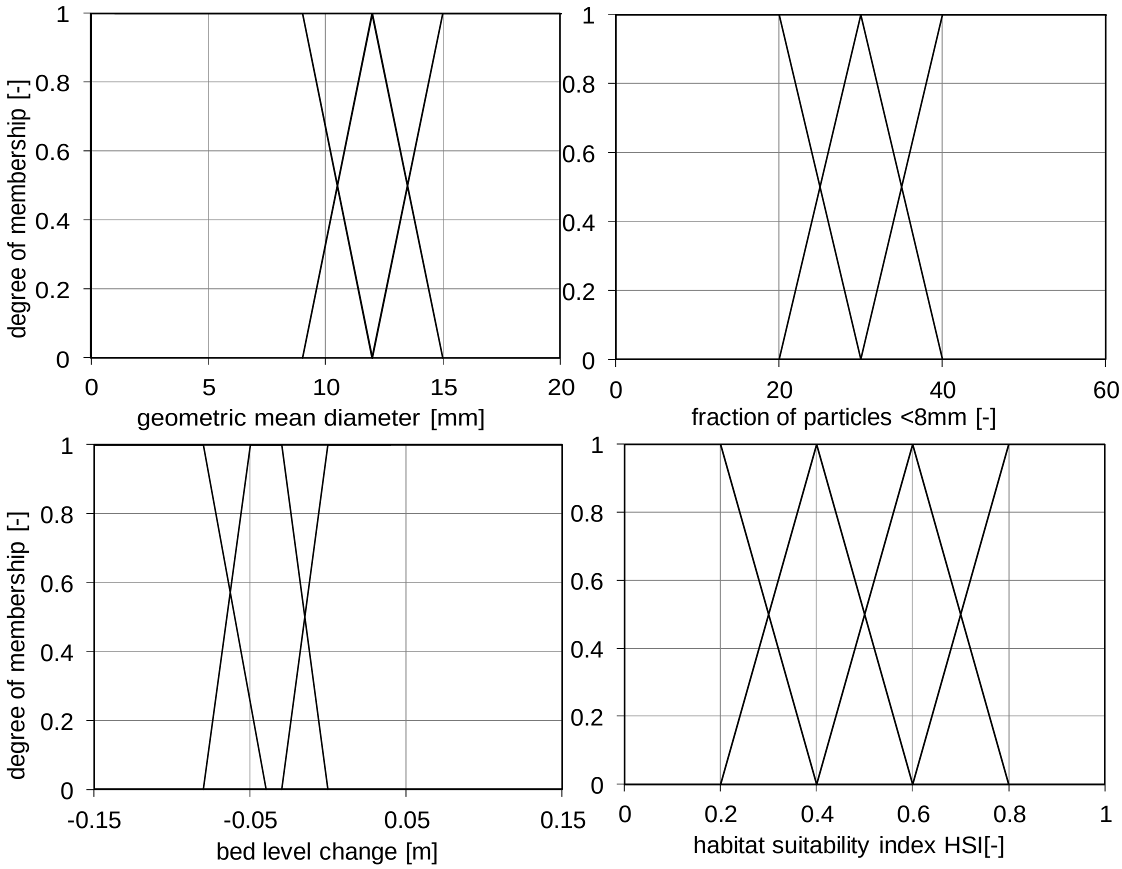


ID	IHS	BLC	VHG	HSI_{inc}
1	L	L	L	L
2	L	L	M	L
3	L	L	H	L
4	L	M	L	L
5	L	M	M	L
6	L	M	H	L
7	L	H	L	L
8	L	H	M	L
9	L	H	H	L
10	M	L	L	L
11	M	L	M	L
12	M	L	H	L
13	M	M	L	L
14	M	M	M	L
15	M	M	H	M
16	M	H	L	L
17	M	H	M	M
18	M	H	H	M

ID	IHS	BLC	VHG	HSI_{inc}
19	H	L	L	L
20	H	L	M	L
21	H	L	H	L
22	H	M	L	L
23	H	M	M	M
24	H	M	H	M
25	H	H	L	L
26	H	H	M	H
27	H	H	H	H
28	VH	L	L	L
29	VH	L	M	L
30	VH	L	H	L
31	VH	M	L	L
32	VH	M	M	M
33	VH	M	H	M
34	VH	H	L	L
35	VH	H	M	H
36	VH	H	H	VH

IHS = interstitial habitat suitability	BLC = bed level change [m]
VHG = vertical hydraulic gradient [-]	HSI = habitat suitability index [-]

Appendix 2.8: Fuzzy-sets and fuzzy-rule-system to compute the habitat suitability index during emergence period (HSI_{emerg}) of brown trout.



ID	p<8mm	d_g	BLC	HSI
1	L	L	L	L
2	L	L	M	L
3	L	L	H	L
4	L	M	L	L
5	L	M	M	M
6	L	M	H	M
7	L	H	L	L
8	L	H	M	M
9	L	H	H	VH
10	M	L	L	L
11	M	L	M	L
12	M	L	H	L
13	M	M	L	L
14	M	M	M	M

ID	p<8mm	dg	BLC	HSI
15	M	M	H	M
16	M	H	L	L
17	M	H	M	M
18	M	H	H	H
19	H	L	L	L
20	H	L	M	L
21	H	L	H	L
22	H	M	L	L
23	H	M	M	L
24	H	M	H	L
25	H	H	L	L
26	H	H	M	L
27	H	H	H	L

p<8mm = fraction of particle sizes < 8mm [%]
d_g = geometric mean diameter [m]

BLC = bed level change [m]
HSI = habitat suitability index [-]

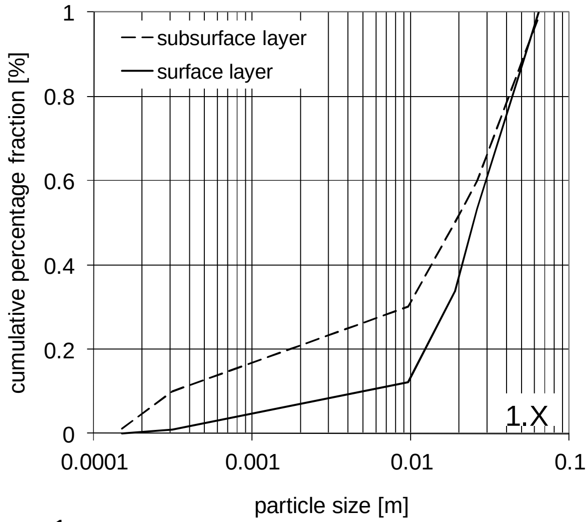
Appendix 3 – simulation of sediment infiltration in the laboratory flume

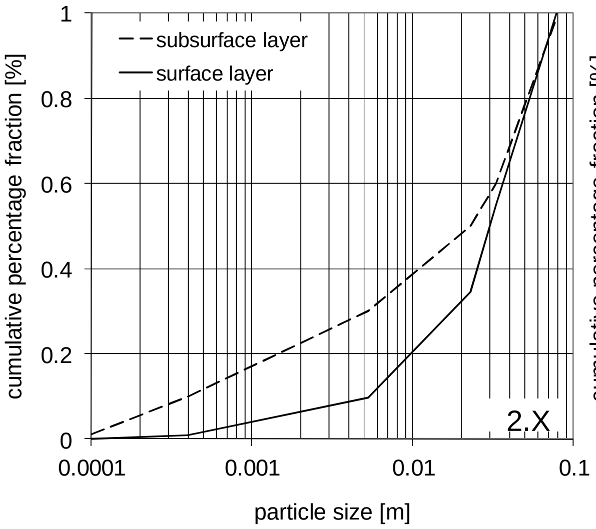
Appendix 3.1: Equations of Guenter (1971) to calculate the coarse surface layer based on the particle size distributions of the subsurface

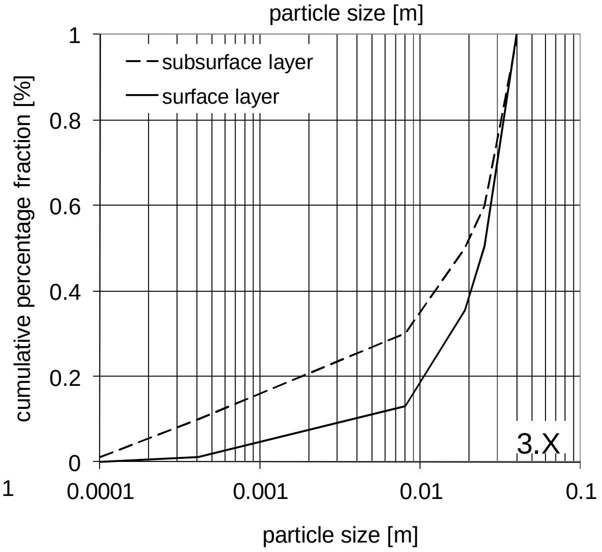
$$\Delta p_{(D_x),i} = \frac{\Delta p_{(D_F),i} \cdot \left[\left(\frac{\Delta p_{(A_x),i}}{\Delta p_{(A_F),i}}\right) \cdot \left(\frac{1 - p_{(A_F),i}}{1 - p_{(A_x),i}}\right)\right]}{\sum_{i=1}^{n} \left[\Delta p_{(D_F),i} \cdot \left(\frac{\Delta p_{(A_x),i}}{\Delta p_{(A_F),i}}\right) \cdot \left(\frac{1 - p_{(A_F),i}}{1 - p_{(A_x),i}}\right)\right]}$$

$$\Delta p_{(A_F),i} = \sqrt{\frac{d_i}{d_{max}}}$$

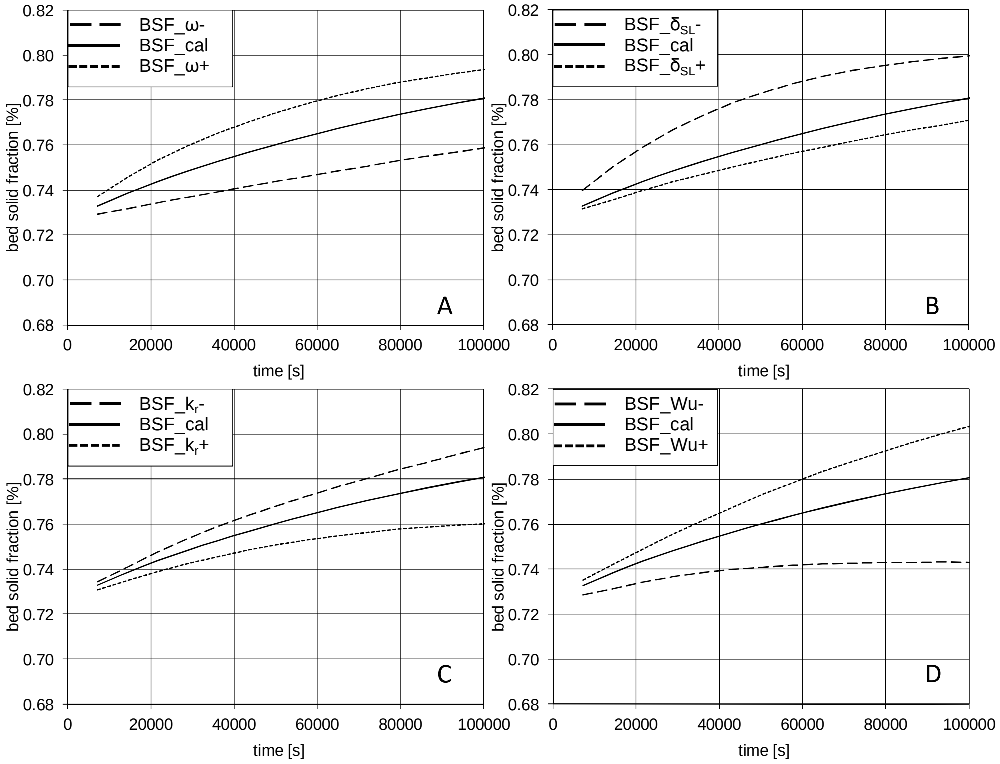
$$\Delta p_{(D_F),i} = 0.67 \cdot \left(\frac{d_i}{d_{max}}\right)^3 + 0.33 \cdot \frac{d_i}{d_{max}}$$



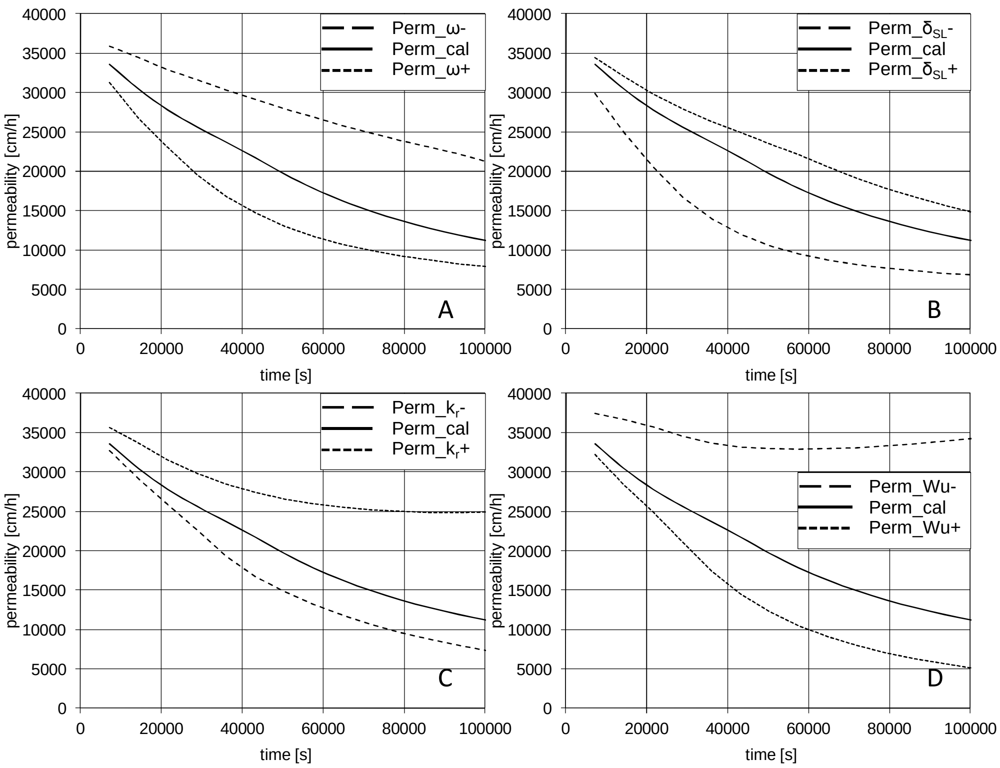




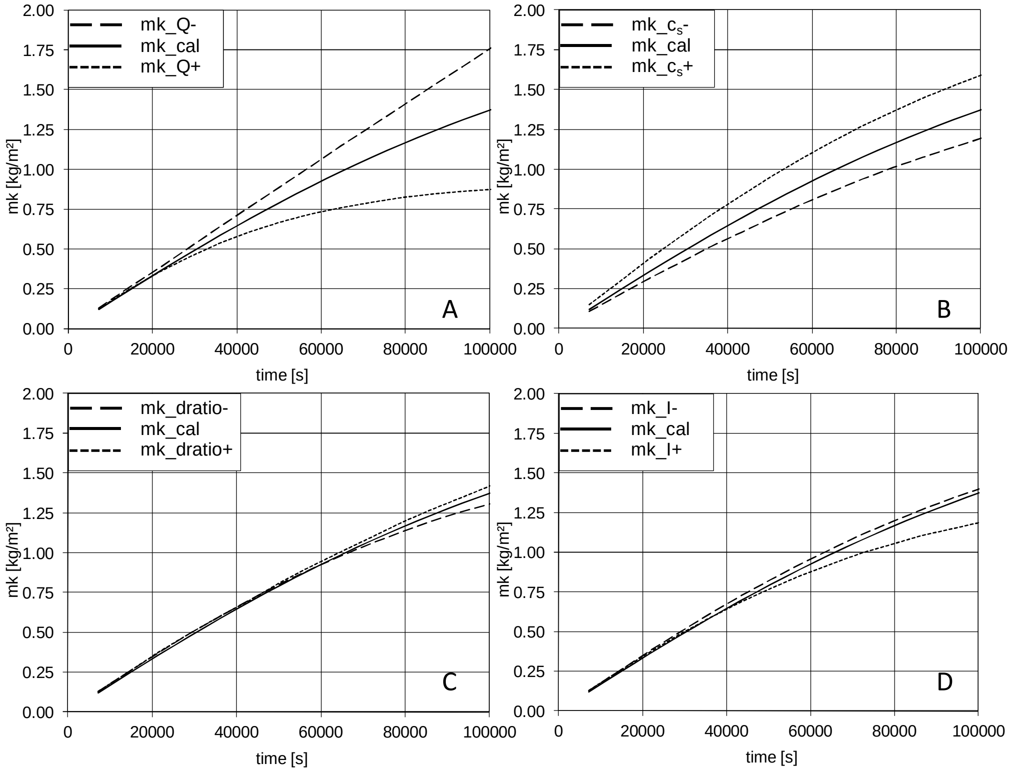
Appendix 3.2: Influence of model-specific parameters on bed solid fraction: A settling velocity, B active layer thickness, C roughness, D exponent hiding/exposure



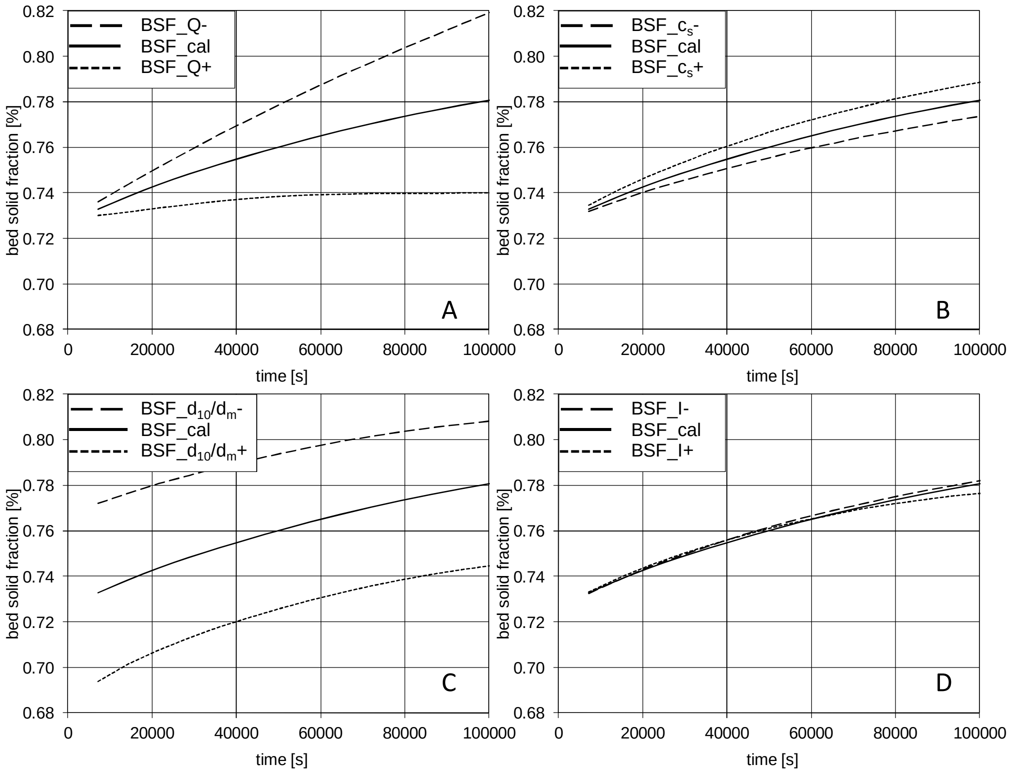
Appendix 3.3: Influence of model-specific parameters on permeability: A settling velocity, B active layer thickness, C roughness, D exponent hiding/exposure



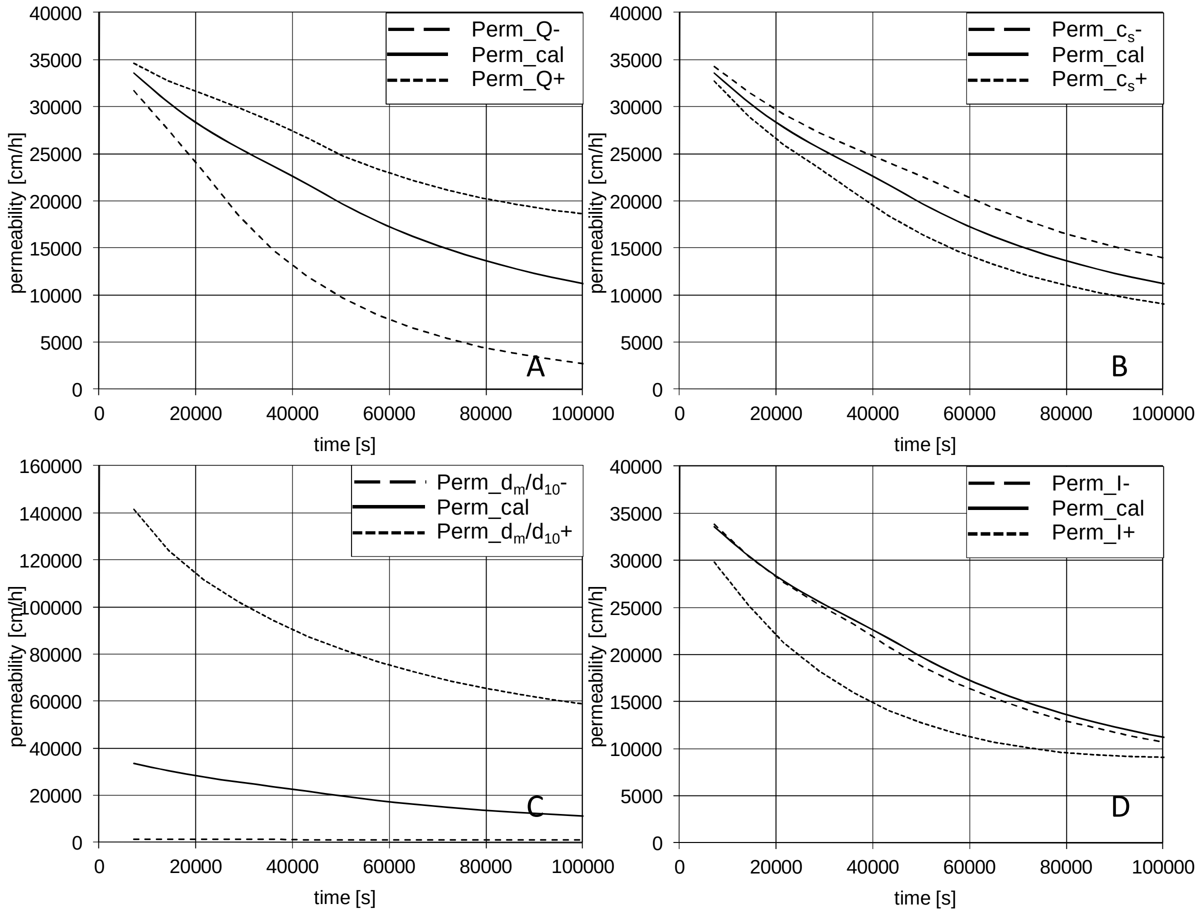
Appendix 3.4 Influence of input parameters on sediment infiltration: A discharge, B sediment concentration, C ratio d_{10}/d_m, D slope



Appendix 3.5: Influence of input parameters on bed solid fraction: A discharge, B sediment concentration, C ratio d_{10}/d_m, D slope



Appendix 3.6: Influence of input parameters on permeability: A discharge, B sediment concentration, C ratio d_{10}/d_m, D slope



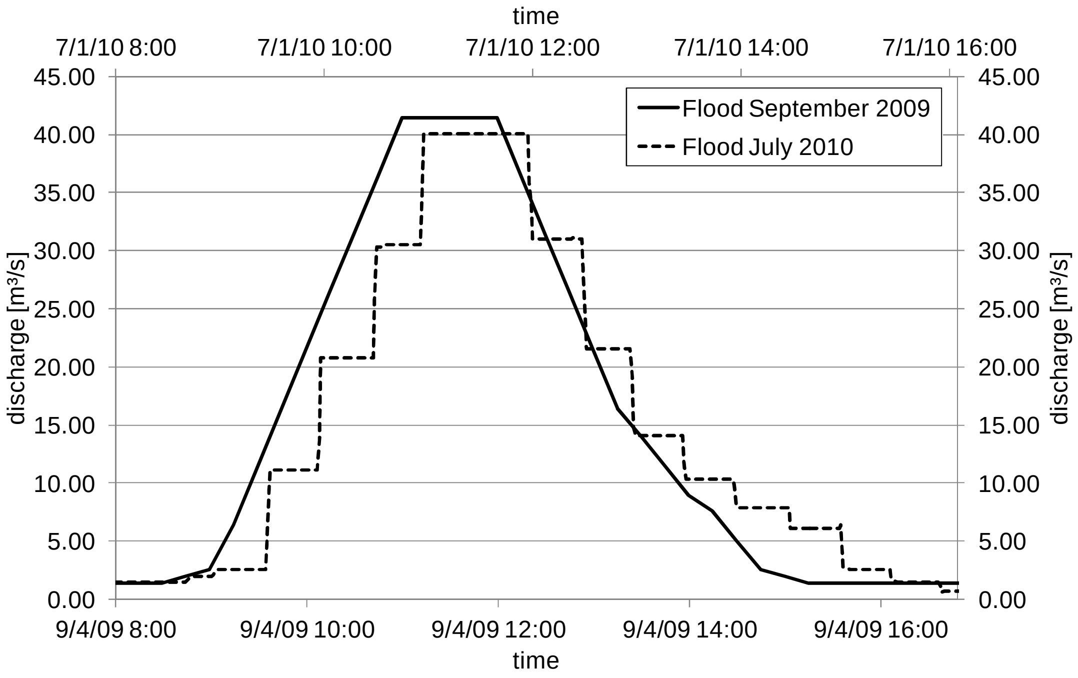
Appendix 4 – abiotic and biotic monitoring in the River Spoel

Appendix 4.1: Temporal overview of the abiotic and biotic monitoring program in the River Spoel.

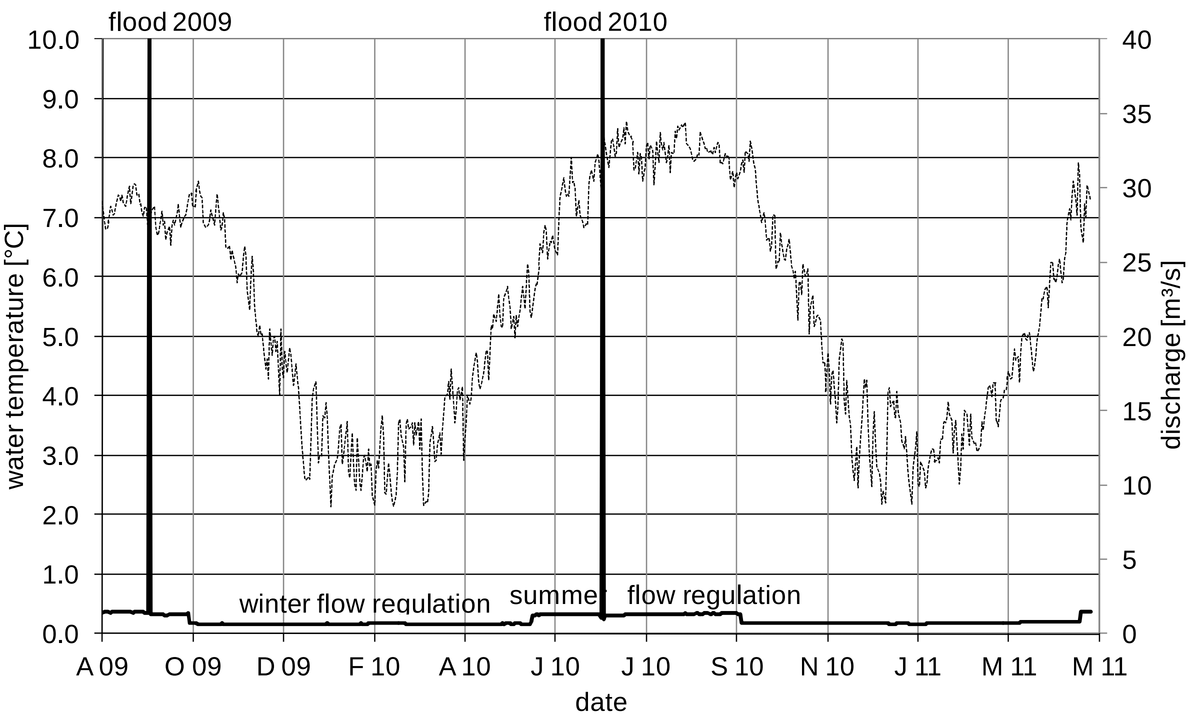
	2.9.09	3.9.09	4.9.09	5.9.09	10.12.09	11.12.09	10.1.10	4.2.10	23.2.10	24.3.10	11.5.10	12.5.10	13.5.10
Topography	x												
Hydraulic data	x		x										
Sediment samples		x (BS)		x (BS)		x (BS)						x (FC)	
Suspended load													
Turbidity													
Dissolved oxygen					x		x	x	x	x	x		
Groundwater levels													
Mapped cover													
Artificial redds						x							
Control hatching									x				
Control emergence													x

	29.06.10	30.06.10	01.07.10	02.07.10	14.07.10	24.08.10	29.09.10	02.11.10	14.12.10	15.12.10	16.02.11	10.05.11	11.05.11
Topography	x			x									
Hydraulic data	x		x	x									
Sediment samples		x (FC)		x (FC)						x (FC)		x (FC)	
Suspended load			x				x						
Turbidity			x				x		x				
Dissolved oxygen	x				x	x	x	x			x		x
Groundwater levels							x						
Mapped cover								x					
Artificial redds									x				
Control hatching											x		
Control emergence													x

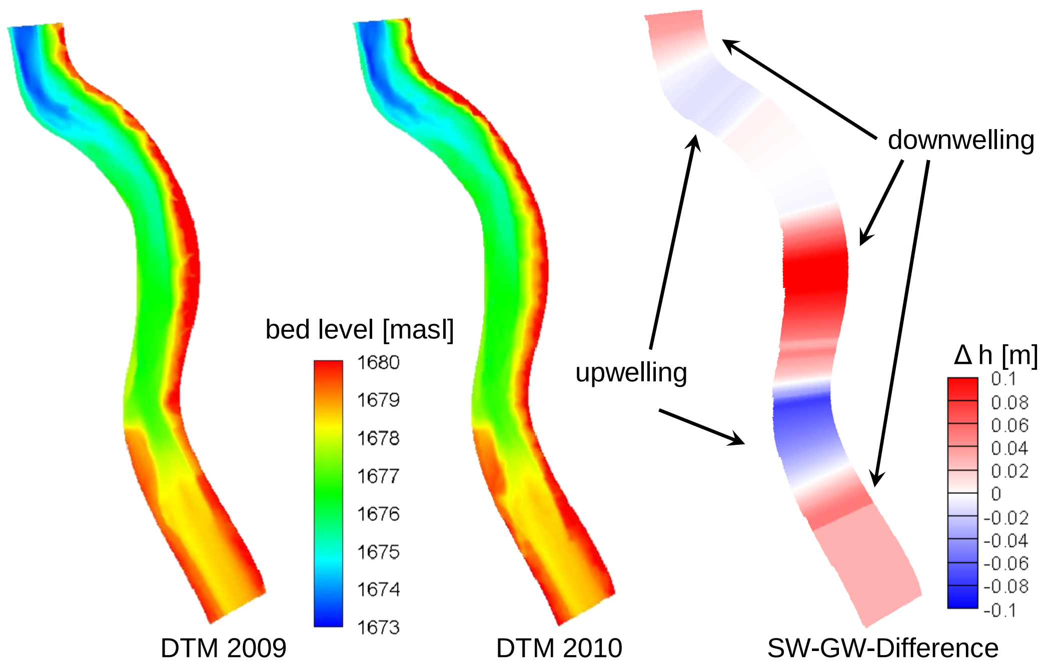
Appendix 4.2: Artificial floods during the monitoring periods 2009/2010 and 2010/2011. Flooding in 2009 was on 04.09.2009 while in 2010 it was on 01.07.2010.



Appendix 4.3: Flow Hydrograph with both artificial floods and the different flow regulation during summer and winter (measured at the gauge station Punt dal Gall) plus the time series of water temperature measured 1200 m downstream of the study site in the River Spoel.



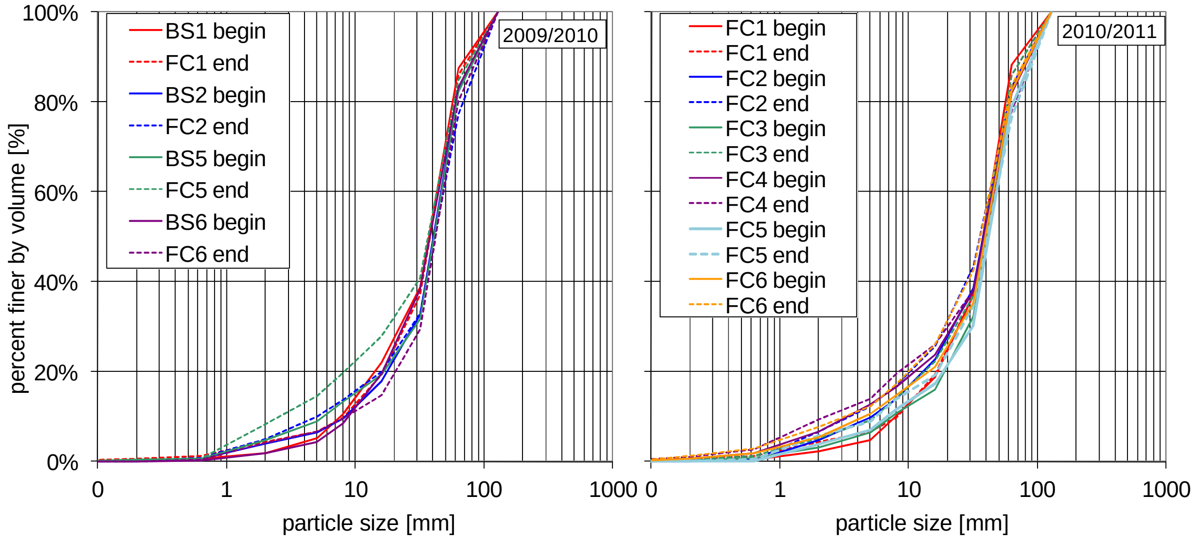
Appendix 4.4: Results of topographical measurements (DTM 2009, DTM2010) and groundwater monitoring: Figured are the bed levels before the artificial floods and the differences of surface water levels with groundwater levels. Positive values indicate downwelling while negative values indicate upwelling.



Appendix 4.5: Particle size analyses of sediment samples before and after artificial flooding in 2009 and 2010. Listed are the minimum, the mean and the maximum values.

	2009						2010					
	before			after			before			after		
	min	mean	max	min	mean	max	min	mean	max	min	mean	max
d_g [mm]	27.8	31.5	35.7	29.6	32.5	34.7	28.9	32.6	36.8	28.2	29.8	31.5
d_m [mm]	39.8	44.3	46.7	41.0	44.1	45.3	41.8	45.0	50.5	41.4	43.5	48.1
SO [-]	2.0	2.5	3.1	2.1	2.2	2.4	2.0	2.4	2.6	2.1	2.6	3.0
d_{10} [mm]	4.3	6.7	8.7	5.7	7.8	9.5	5.4	6.8	8.4	4.1	5.7	7.8
d_{50} [mm]	44.1	48.1	49.8	38.8	41.6	42.8	39.1	42.0	46.6	39.5	40.7	44.1
d_{90} [mm]	76.2	89.7	98.9	76.3	86.6	91.3	82.4	90.5	103	72.3	87.5	102
$p_{<2mm}$	2.7	3.9	6.5	1.8	3.1	4.8	3.1	3.9	4.5	2.3	4.5	6.7

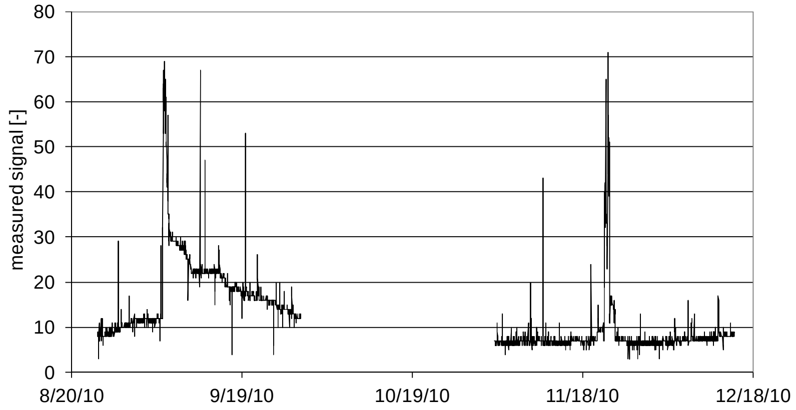
Appendix 4.6: Particle size distributions of monitoring the infiltration periods in 2009/2010 and 2010/2011: The monitoring period in 2009/2010 encompassed 250 days, the period in 2010/2011 313 days.



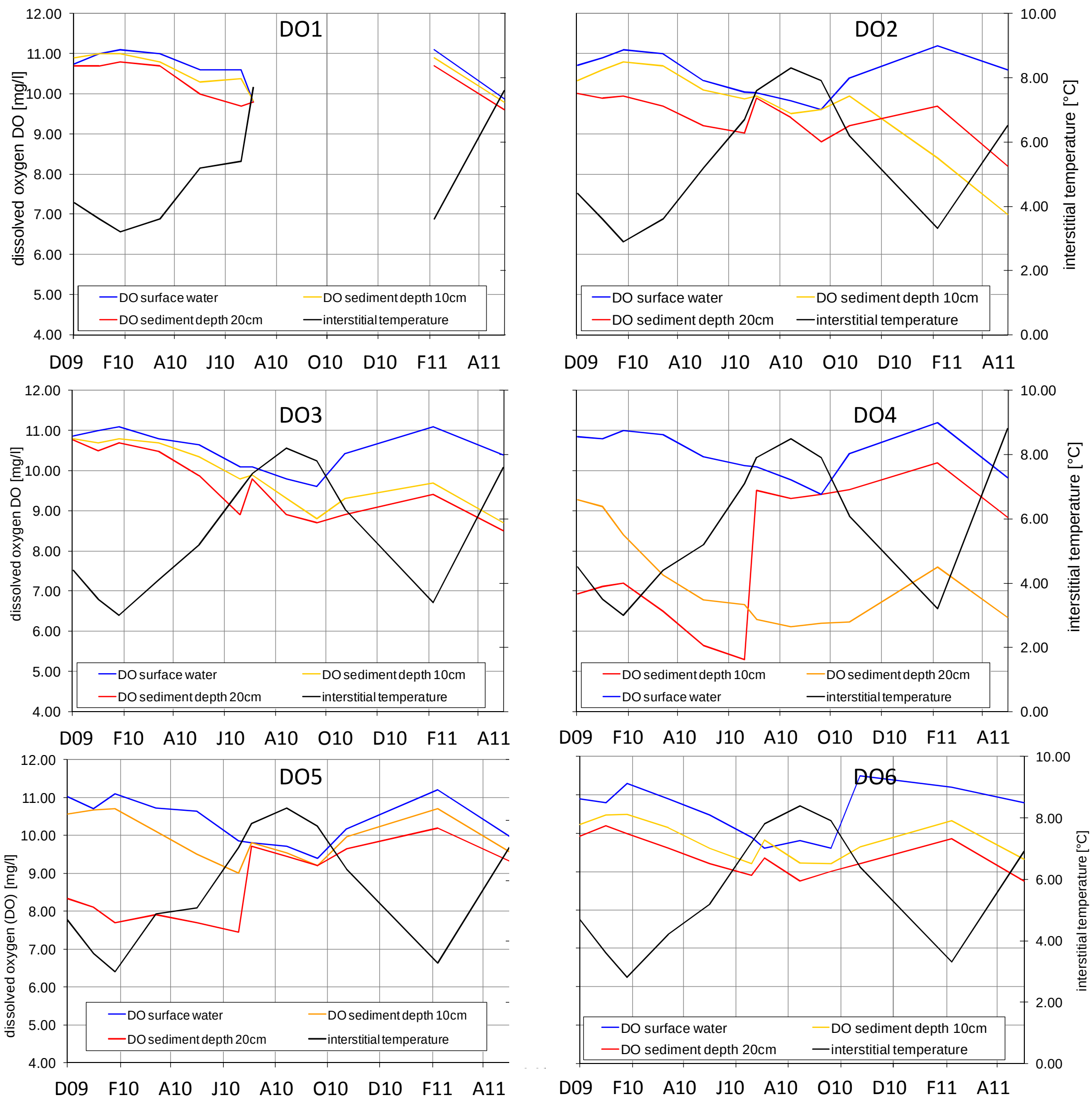
Appendix 4.7: Particle size analyses of sediment samples at the beginning of monitoring sediment infiltration (after artificial flooding) until end of reproduction period. Listed are the minimum, the mean and the maximum values.

	2009						2010					
	09/05/2009			05/12/2010			07/02/2010			05/10/2011		
	min	mean	max	min	mean	max	min	mean	max	min	mean	max
d_g [mm]	29.6	32.5	34.7	23.3	31.4	36.8	28.2	29.8	31.5	24.7	26.8	33.2
d_m [mm]	41.0	44.1	45.3	40.1	44.5	47.5	41.4	43.5	48.1	40.7	41.6	43.0
SO [-]	2.1	2.2	2.4	2.0	2.5	3.3	2.1	2.6	3.0	2.0	2.8	3.6
d_{10} [mm]	5.7	7.8	9.5	2.8	6.6	9.9	4.1	5.7	7.8	2.5	5.0	9.6
d_{50} [mm]	38.8	41.6	42.8	38.1	41.7	44.3	39.5	40.7	44.1	36.8	39.1	40.9
d_{90} [mm]	76.3	86.6	91.3	81.3	90.2	99.4	72.3	87.5	102	78.5	87.2	98.3
$p_{<2mm}$	1.8	3.1	4.8	2.5	5.0	8.2	2.3	4.5	6.7	3.7	6.5	9.3

Appendix 4.8: Results of turbidity monitoring: Figured is the measured signal which is a voltage that is proportional to the dispersion degree of reflected light.



Appendix 4.9: Results of dissolved oxygen monitoring: Figured are the dissolved oxygen concentrations of surface water and of sediment depths in 10 cm and 20 cm plus the simultaneously measured interstitial temperature.

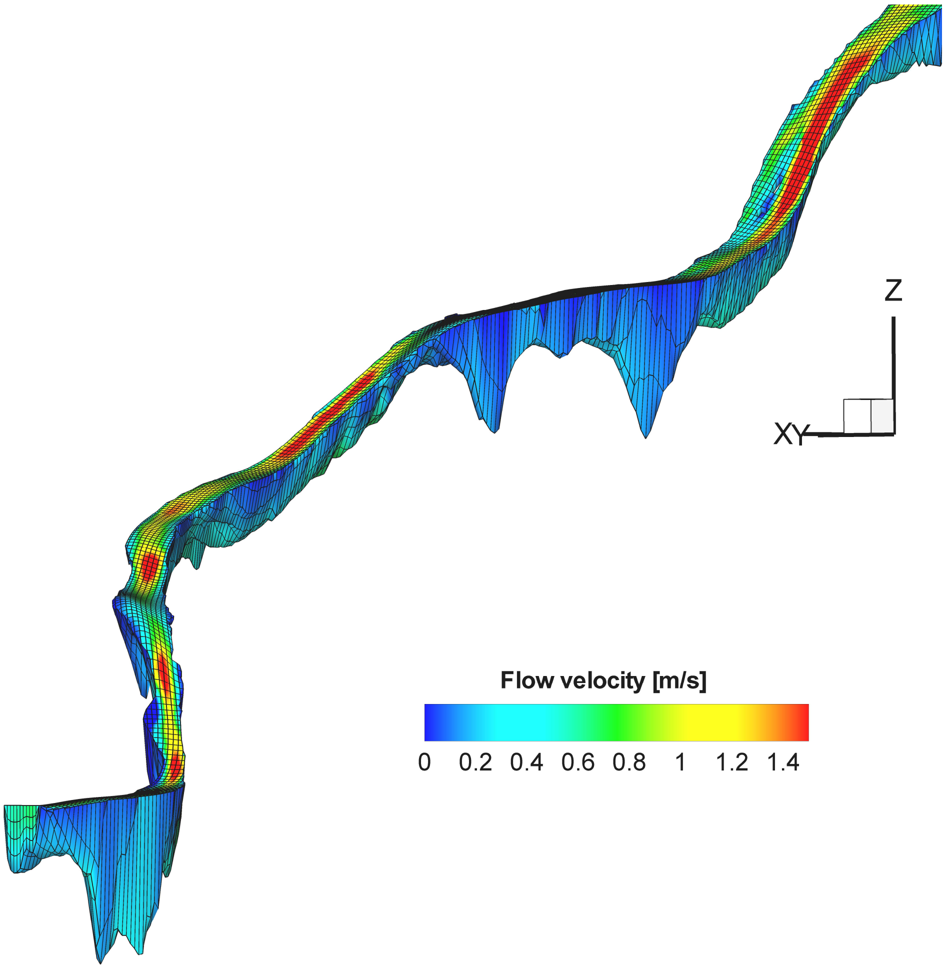


Appendix 4.10: Result of monitoring the survival rates from the eyed-egg stage to hatching for season 2009-2010 and season 2010-2011.

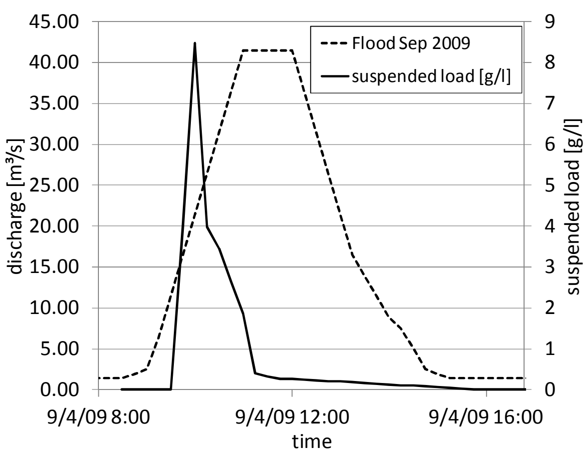
	season 2009-2010				season 2010-2011			
	caps. 1 [%]	caps. 2 [%]	caps. 3 [%]	mean [%]	caps. 1 [%]	caps. 2 [%]	caps. 3 [%]	mean [%]
AR 1	90	80	100	90	60	80	30	57
AR 2	90	40	80	70	30	70	90	63
AR 3	40	60	40	47	70	20	80	57
		mean survival SP1		**71**		**mean survival SP1**		**59**
AR 4	80	60	70	70	90	50	60	67
AR 5	70	70	60	70	80	90	60	77
AR 6	90	70	100	87	90	60	50	67
		mean survival SP2		**74**		**mean survival SP2**		**70**
AR 7	-	-	-	-	30	60	60	50
AR 8	70	60	70	67	60	0	50	55
AR 9	80	70	80	77	70	70	40	60
		mean survival SP3		**72**		**mean survival SP3**		**55**
	total survival 2009-2010			**72**	**total survival 2010-2011**			**61**

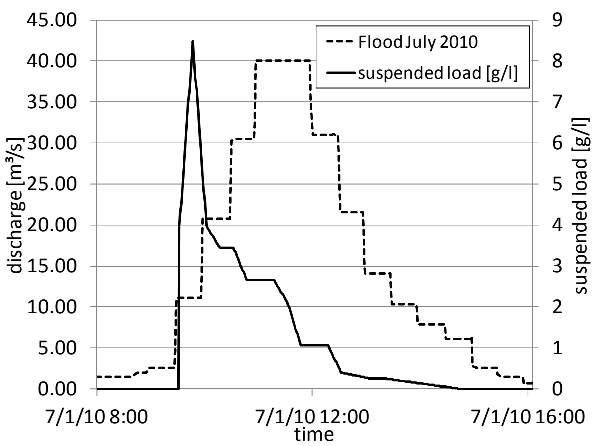
Appendix 5 – morphodynamic simulation of artificial

Appendix 5.1: Exemplary visualisation of the unstructured adaptive grid of SSIIM2 in three dimensions: The grid is applied for all numerical simulation in the case study River Spoel. Illustrated are the flow velocities in y-direction.

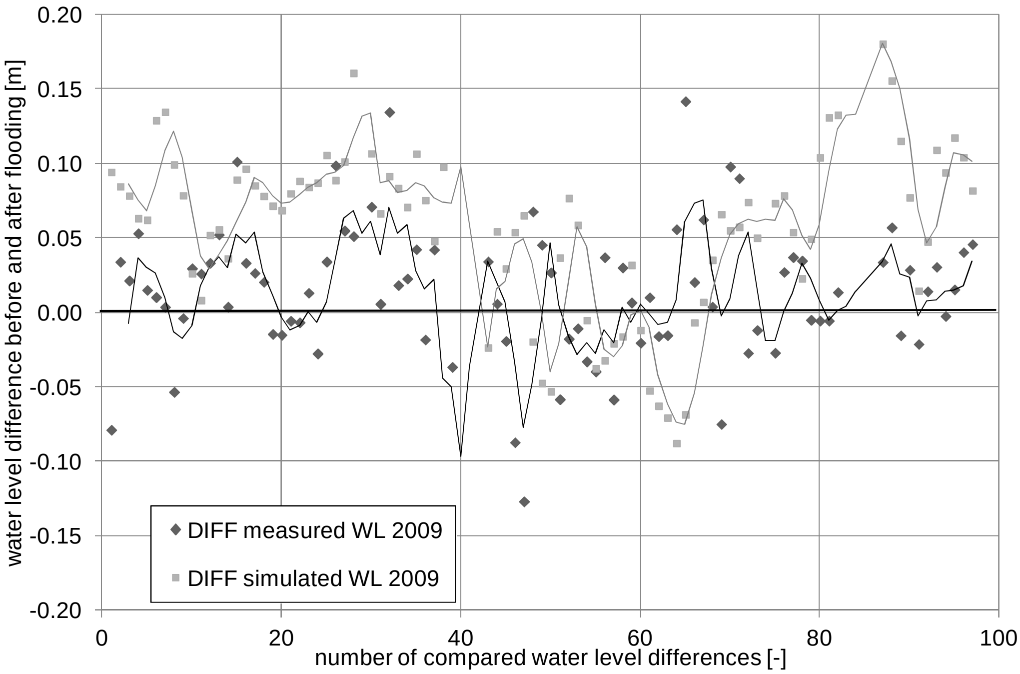


Appendix 5.2: Artificial flooding with boundary conditions for sediment fluxes in 2009 and 2010.





Appendix 5.3: Comparison of measured and simulated water level difference before and after the artificial flooding in September 2009.



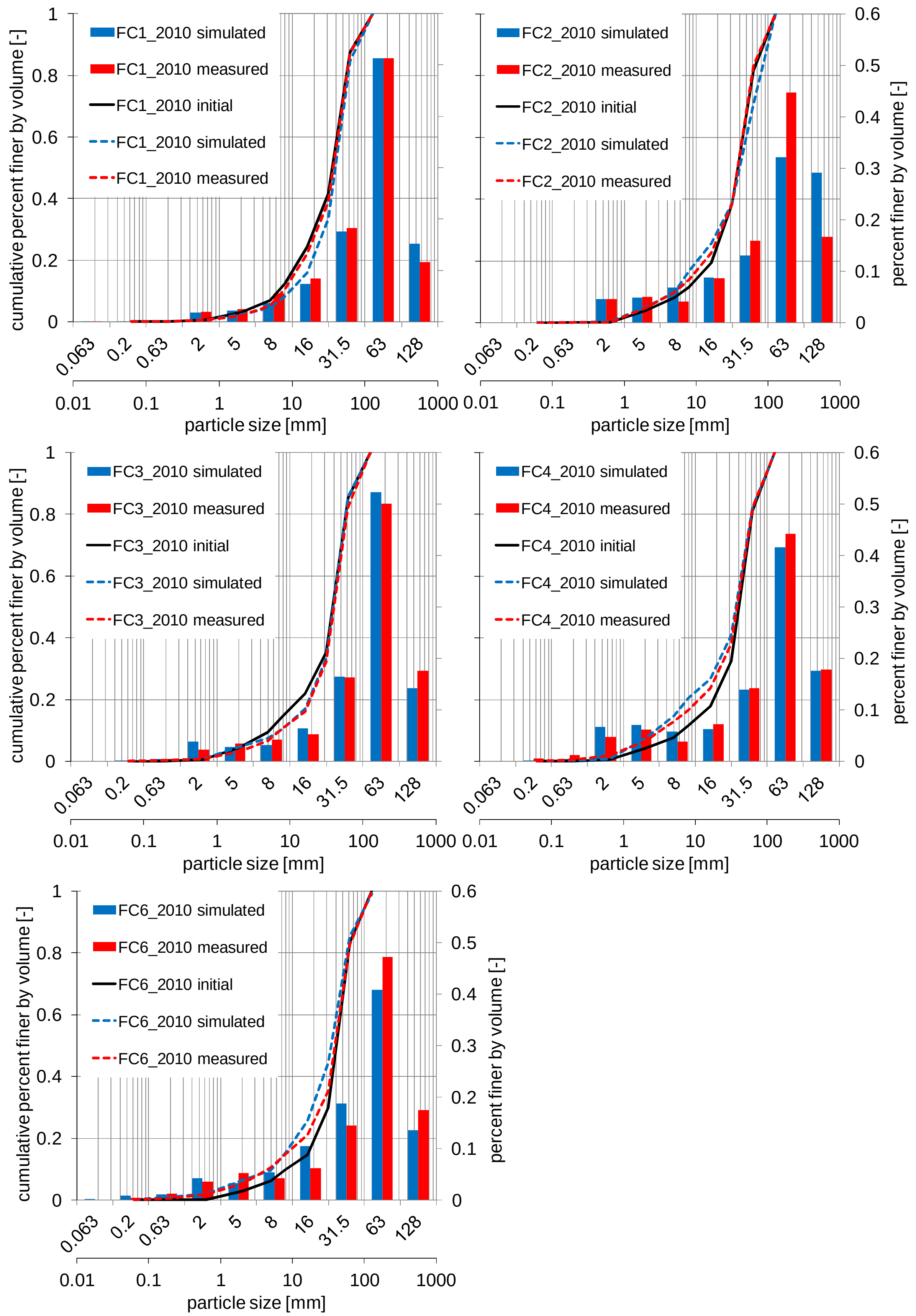
Appendix 5.4: Summarized model specifications in SSIIM2 for simulating artificial flooding in 2009 and 2010.

t [s]	Iterations	ρ_s[kg/m³]	θ[-]	k_s [m]	q_b
3	200	2.65	0.065	0.3	Wu et al. (2000)
δ_{SL}[m]	δ_{ML} [m]	m [-]	no. particles	ω_s [m/s]	h_{min} [m]
0.15	5.0	0.3	10	Zhang (1961)	0.05

Appendix 5.5: Comparison of typical particle size analyses for measured and simulated particle size distributions during artificial flooding in 2010.

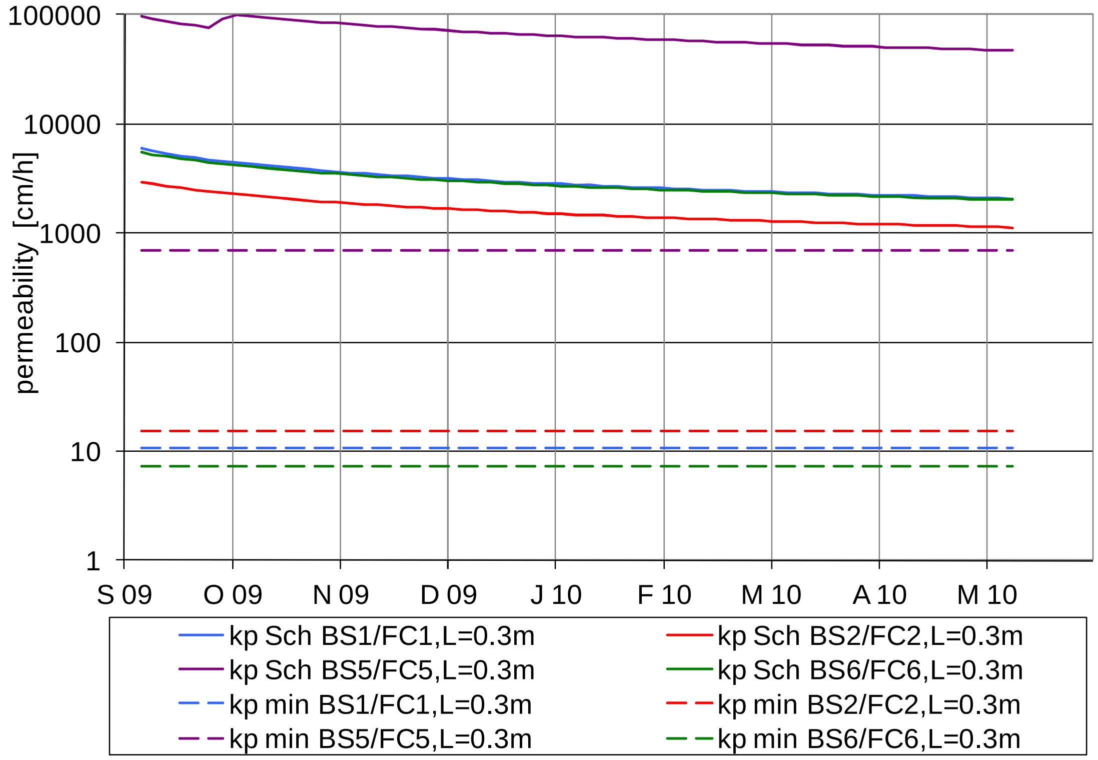
	FC1		FC2		FC3		FC4		FC6	
	meas	sim	meas	sim	meas	sim	meas	sim	meas	sim
d_g [mm]	29.6	34.3	28.8	30.0	34.2	32.6	27.0	24.4	29.4	26.3
d_m [mm]	41.0	44.4	42.6	48.1	45.6	43.6	42.9	41.5	43.8	39.7
SO [-]	2.3	2.0	2.6	3.4	2.1	2.1	3.0	3.5	2.7	2.7
d_{10} [mm]	7.6	9.7	5.1	5.0	7.4	7.4	3.6	3.1	4.7	5.1
d_{50} [mm]	38.7	41.7	39.6	42.5	42.6	41.5	40.1	38.5	41.2	35.8
d_{90} [mm]	76.3	85.5	89.2	105.8	91.2	82.9	91.6	91.4	90.7	83.6
$p_{<2mm}$ [%]	1.9	2.4	4.8	5.1	3.1	4.6	6.7	7.5	7.5	6.3

Appendix 5.6: Comparison of particle size distributions (measured and simulated) after artificial flooding in 2010. Additionally visualized is the initial measured particle size distribution to visualize the effects of artificial flooding.



Appendix 6 – morphodynamic simulation of sediment infiltration

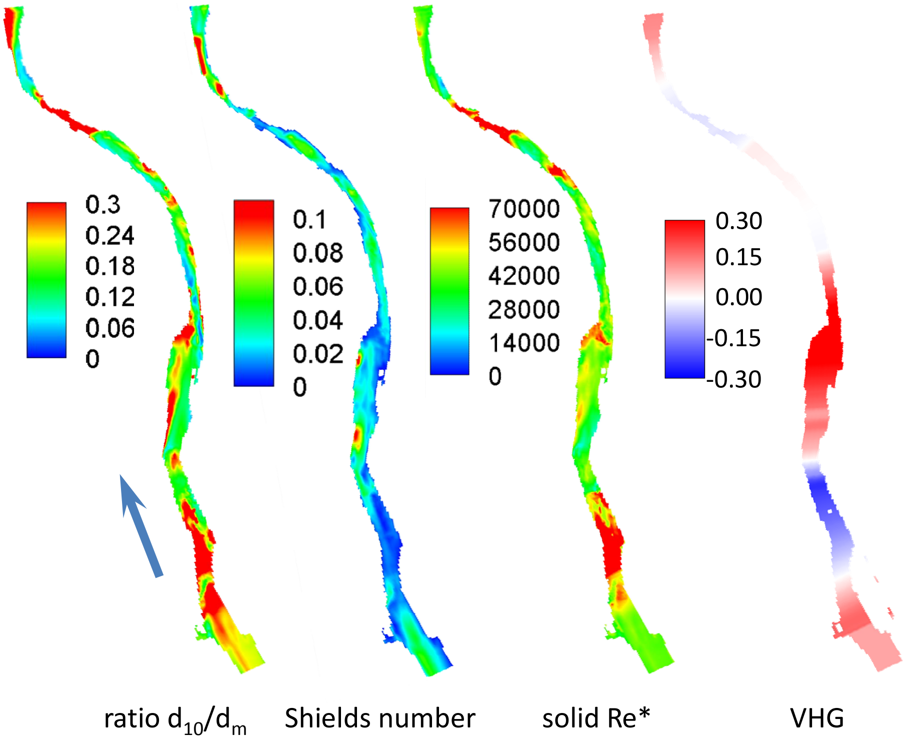
Appendix 6.1: Reductions of permeability due to sediment infiltration simulated with the semi-empirical approach of Schaelchli (1993) using Eq.B.2.13 in the infiltration period 2009/2010. Additional information is provided about the minimum permeabilities in case of equilibrium between deposition and resuspension (Eq.B.2.11, Eq.B.2.14).



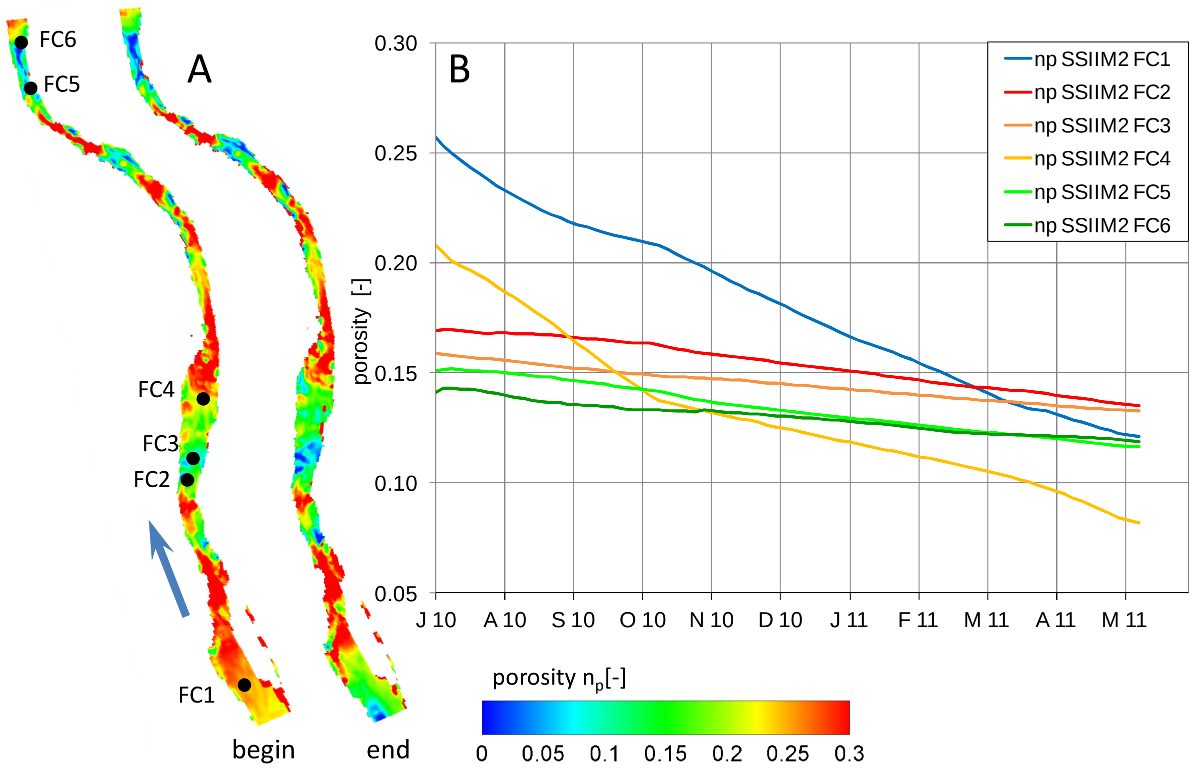
Appendix 6.2: Summarized model specifications in SSIIM2 for simulating sediment infiltration in 2009/2010 and 2010/2011.

t [s]	Iterations	ρ_s[kg/m³]	θ[-]	k_s [m]	q_s
900	200	2.65	Shields Curve	0.3	Van Rijn (1984) Wu et al. 2000)
δ_{SL}[m]	δ_{ML} [m]	m [-]	no. particles	ω_s [m/s]	h_{min} [m]
0.15	5.0	0.7	10	Zhang (1961)	0.05

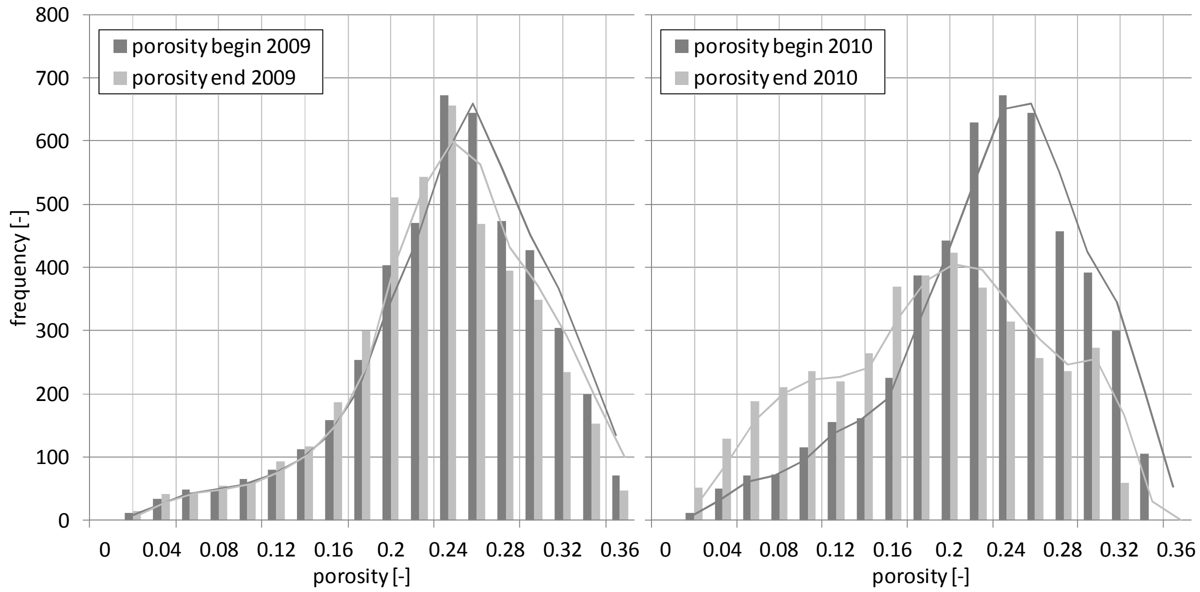
Appendix 6.3: Spatial distributions of input parameters for the semi-empirical approach of Schaelchli (1993) affecting the sediment infiltration masses.



Appendix 6.4: Spatial distribution of porosity at the beginning and end of infiltration period 2010/2011 (A), and the temporal variation of porosity at the sediment samples FC1-FC6 (B).

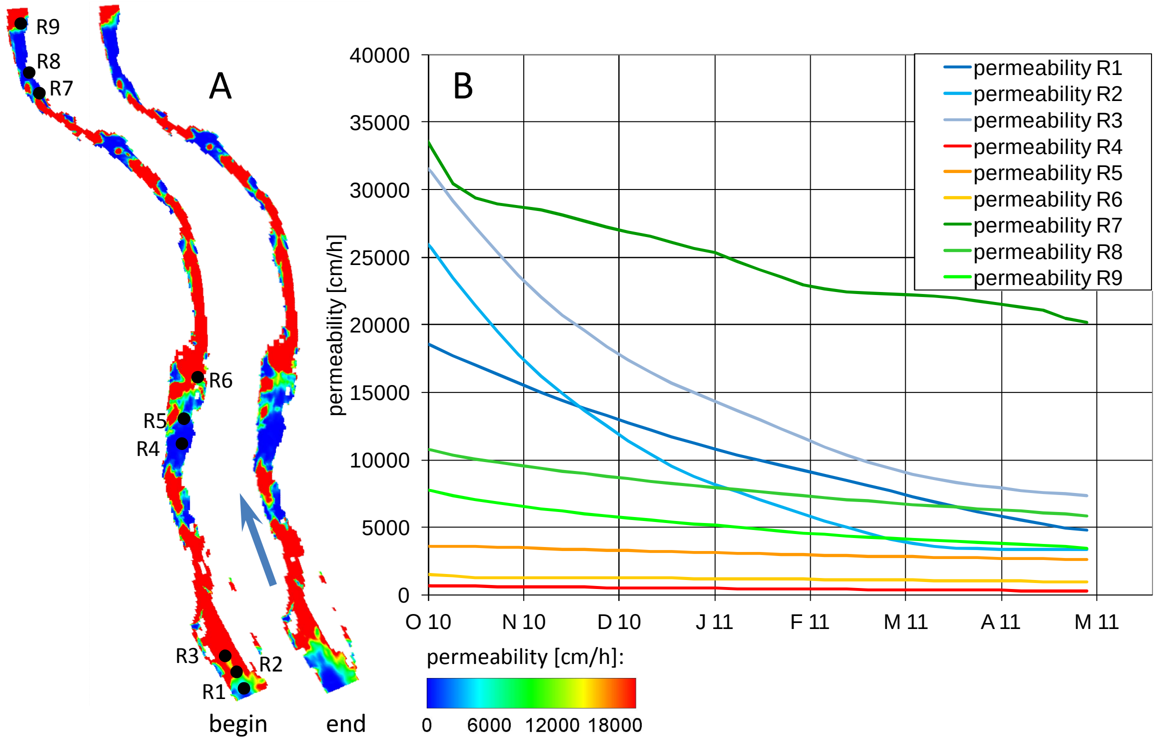


Appendix 6.5: Frequency distributions of simulated porosities (SSIIM2) in both infiltration periods (2009/2010 (left) and 2010/2011 (right)). The lines give the moving average of the frequency values.

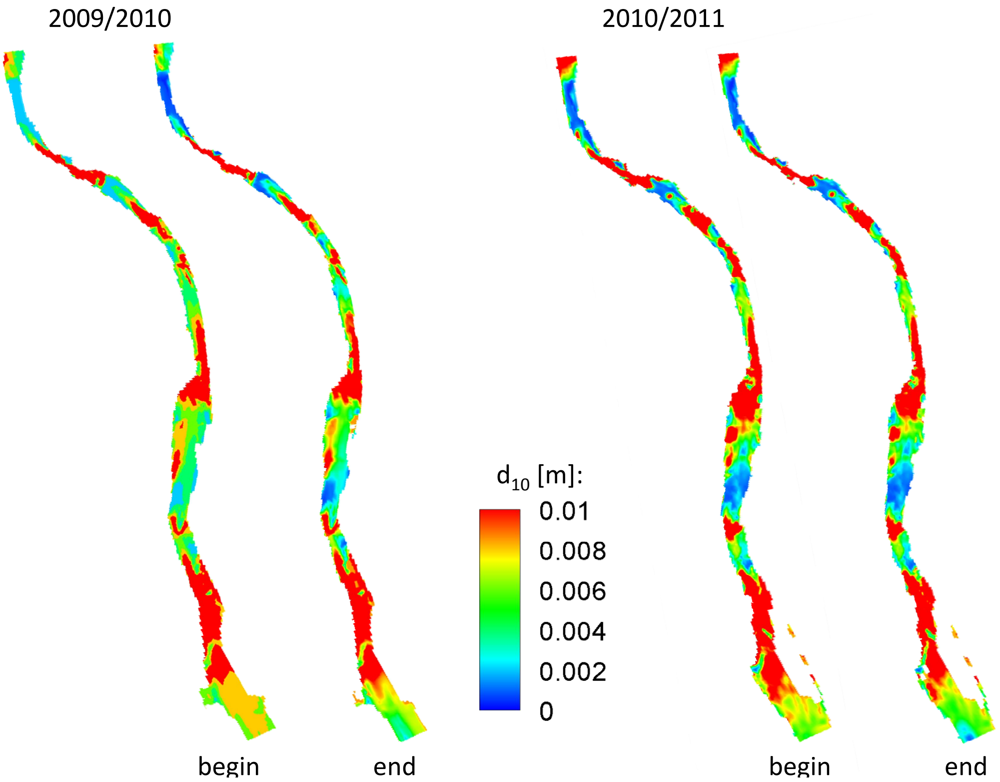


Appendix 7 – simulation of interstitial habitat suitability in River Spoel

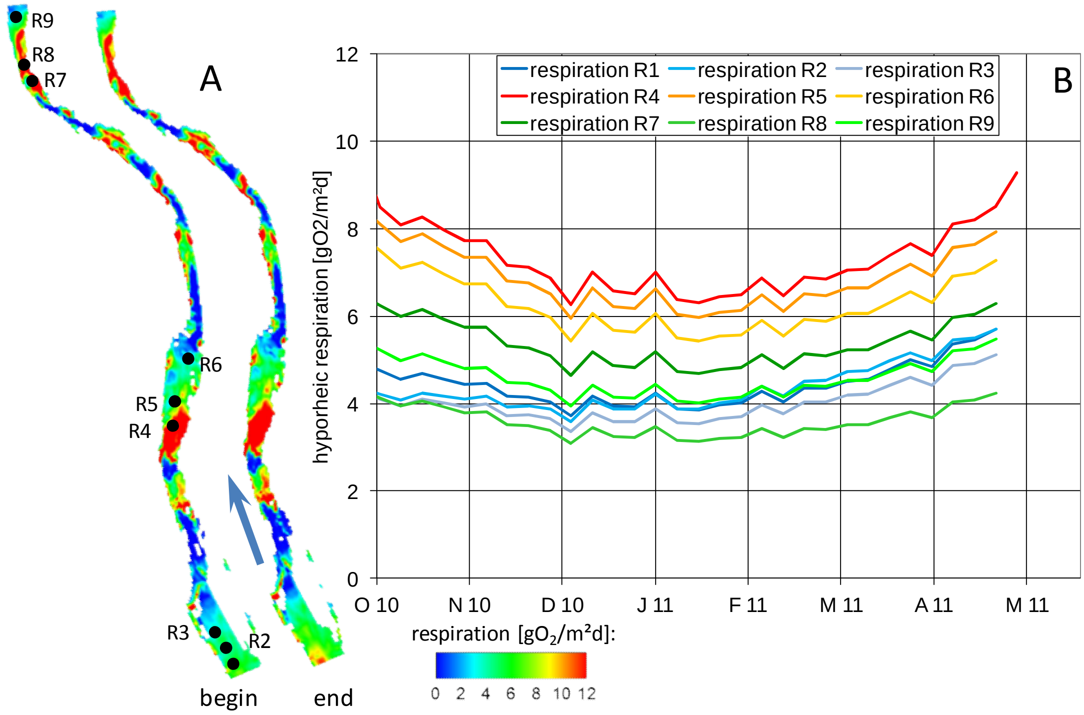
Appendix 7.1: Computed permeabilities in the reproduction period 2010/2011: Plotted are the spatial distribution at the beginning and end of the reproduction period (A), and the time-series of permeabilities for all artificial spawning redds (B).



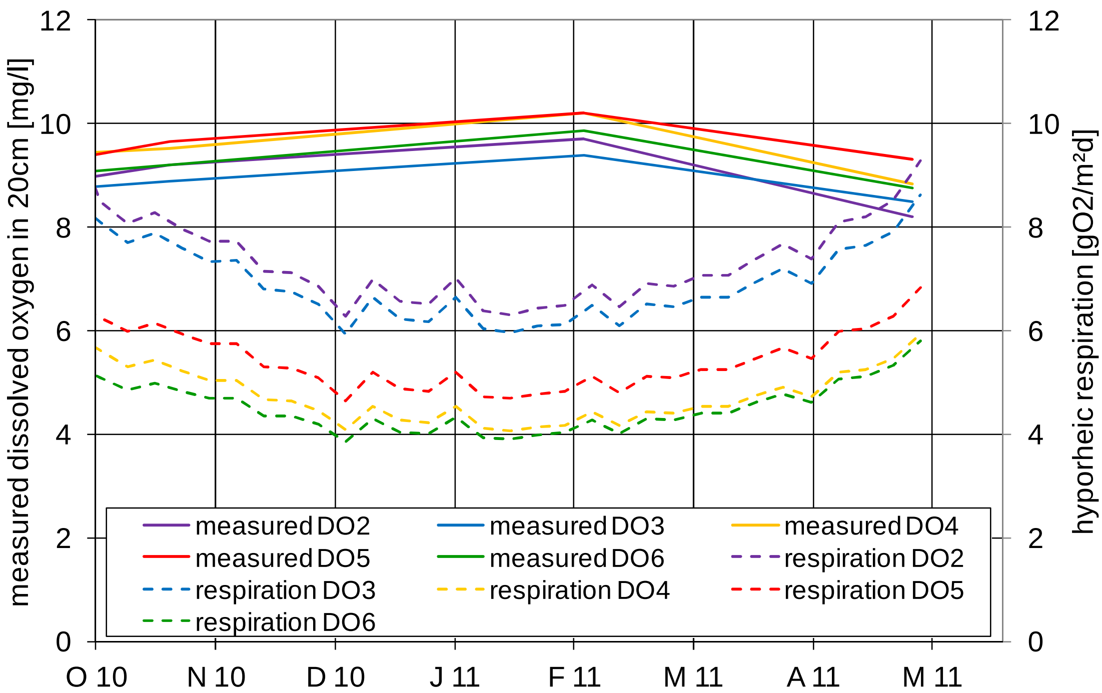
Appendix 7.2: Spatial distribution of simulated values of d_{10} at the beginning and end of both reproduction periods.



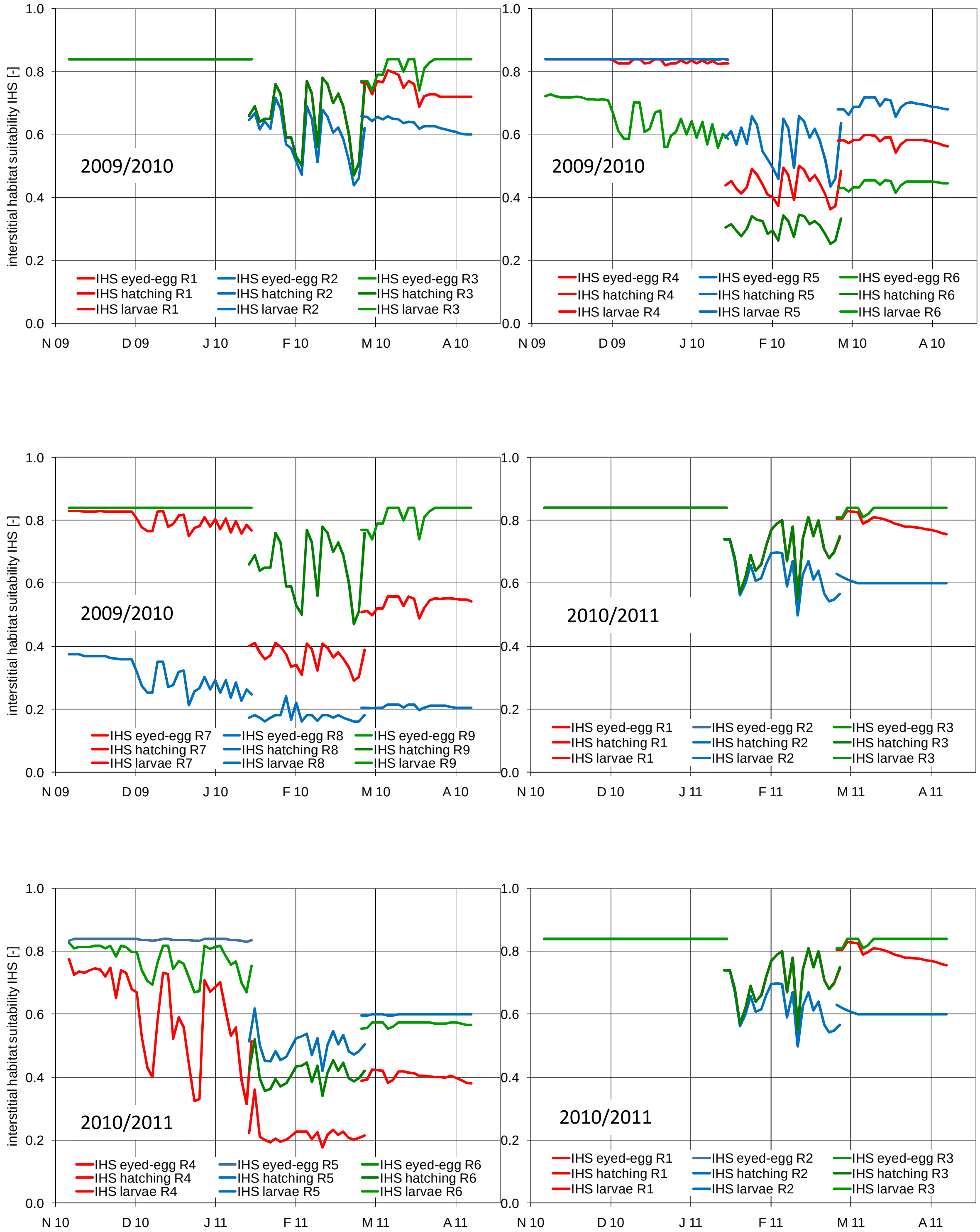
Appendix 7.3: Computed respiration values in the reproduction period 2010/2011. Plotted are the spatial distributions at the beginning and end of the reproduction period (A), and the time-series of respiration values for all artificial spawning redds (B).



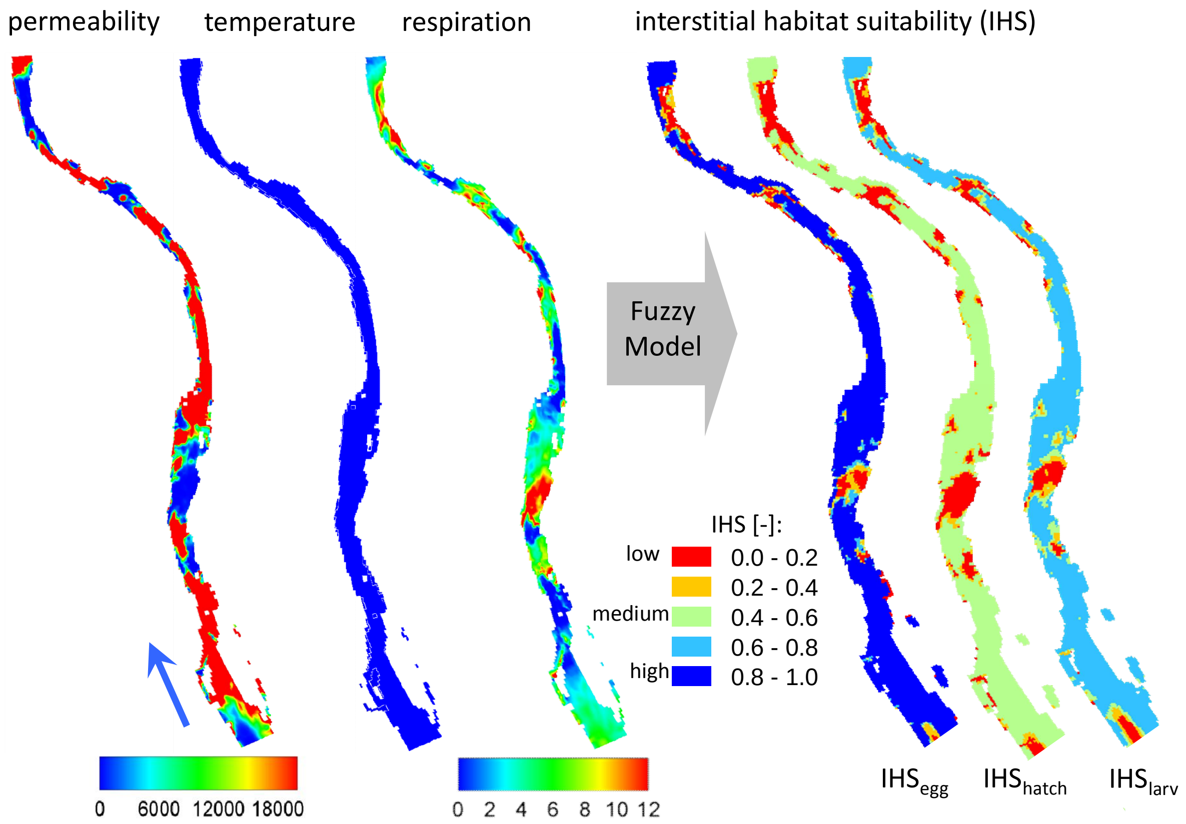
Appendix 7.4: Comparison of measured dissolved oxygen concentration (DO2-DO6) with simulated respiration values for the reproduction period 2010/2011 (different colouring compared to the respiration values in the previous figure).



Appendix 7.5: Time-series of interstitial habitat suitabilities (IHS) in the artificial redds during both incubation period (2009/2010, 2010/2011) for all life-stages (IHS$_{egg}$, IHS$_{hatch}$, IHS$_{larv}$).



Appendix 7.6: Spatial distribution of in- and output data of the fuzzy-approach to simulate the interstitial habitat suitability (IHS) for the life-stages during incubation period 2010/2011:



Appendix 8 – simulation of habitat suitability index for spawning (HSI_{spawn})

Appendix 8.1:
Equations of Crisp (1996) to determine the time-periods for each life-stage during incubation period:

hatching stage $\log_{10} d_{hatching} = [-13.9306 \log_{10}(T + 80)] + 28.8392$

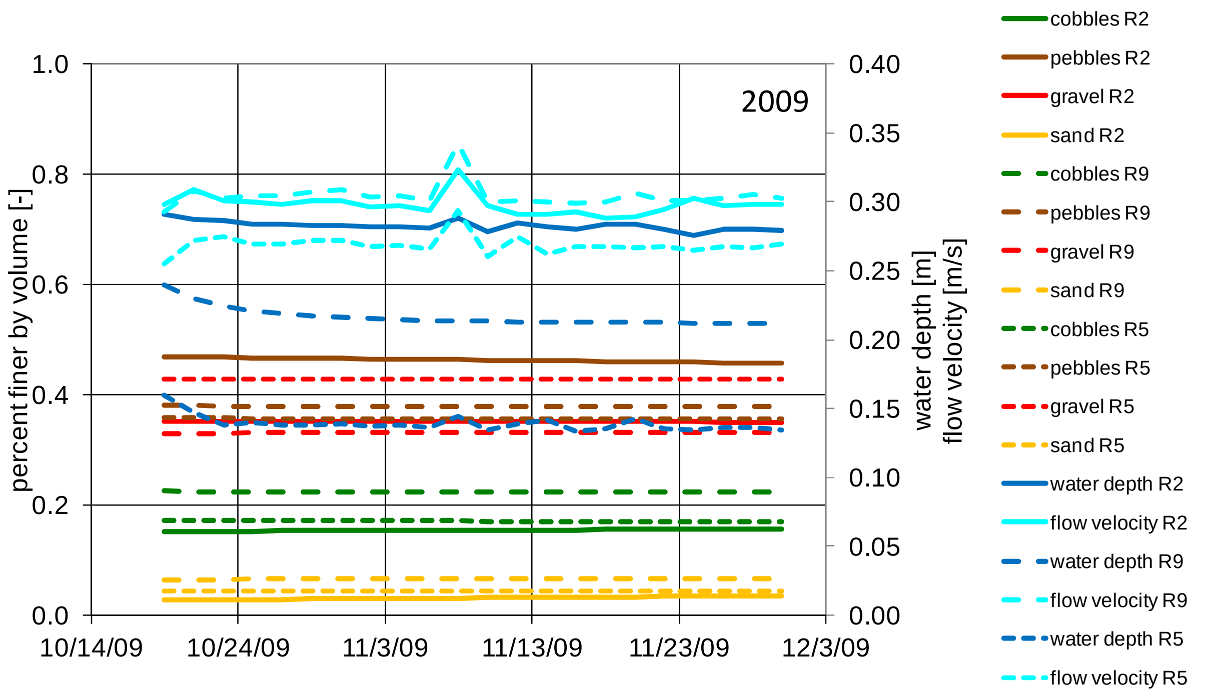
eyed-egg stage: $d_{eyed-egg} = 0.455 \cdot d_{hatching} + 5.0$

emergence stage: $d_{emergence} = 2.0 \cdot d_{hatching}$

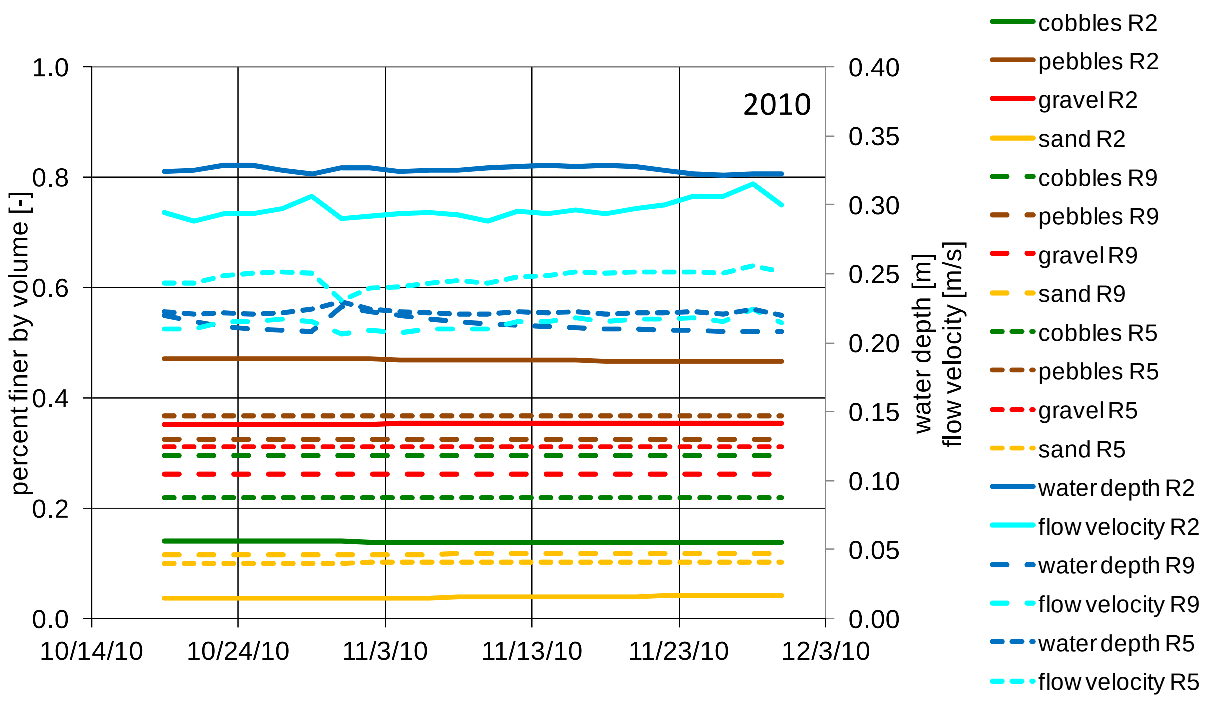
All equations are based on the mean hatching time which includes only the water temperature as input variable. For the artificial redds, the day of installation of the egg-capsules was fixed for the eyed-stage. As the temperature strongly varies between spawning and emergence different calculations using different measured water temperatures were performed resulting in overlapping time periods for each life-stage as it is figured below.

<table>
<tr><th>Date</th><th>Spawning</th><th>Eyed-Egg</th><th>Hatching</th><th>Larvae</th><th>Emergence</th></tr>
<tr><td>14.10.2009/2010</td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td><td></td></tr>
<tr><td>21.10.2009/2010</td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td><td></td></tr>
<tr><td>28.10.2009/2010</td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td><td></td></tr>
<tr><td>04.11.2009/2010</td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td><td></td></tr>
<tr><td>11.11.2009/2010</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>18.11.2009/2010</td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td></tr>
<tr><td>25.11.2009/2010</td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td></tr>
<tr><td>02.12.2009/2010</td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td></tr>
<tr><td>09.12.2009/2010</td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td></tr>
<tr><td>16.12.2009/2010</td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td></tr>
<tr><td>23.12.2009/2010</td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td></tr>
<tr><td>30.12.2009/2010</td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td></tr>
<tr><td>06.01.2010/2011</td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td></tr>
<tr><td>13.01.2010/2011</td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td><td></td></tr>
<tr><td>20.01.2010/2011</td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td><td></td><td></td></tr>
<tr><td>27.01.2010/2011</td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td><td></td><td></td></tr>
<tr><td>03.02.2010/2011</td><td></td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td></tr>
<tr><td>10.02.2010/2011</td><td></td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td></tr>
<tr><td>17.02.2010/2011</td><td></td><td></td><td bgcolor="#c0c0c0"></td><td></td><td></td></tr>
<tr><td>24.02.2010/2011</td><td></td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td><td></td></tr>
<tr><td>03.03.2010/2011</td><td></td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td><td></td></tr>
<tr><td>10.03.2010/2011</td><td></td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td><td></td></tr>
<tr><td>17.03.2010/2011</td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td><td></td></tr>
<tr><td>24.03.2010/2011</td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td><td></td></tr>
<tr><td>31.03.2010/2011</td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td><td></td></tr>
<tr><td>07.04.2010/2011</td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td><td></td></tr>
<tr><td>14.04.2010/2011</td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td></tr>
<tr><td>21.04.2010/2011</td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td><td bgcolor="#c0c0c0"></td></tr>
<tr><td>28.04.2010/2011</td><td></td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td></tr>
<tr><td>05.05.2010/2011</td><td></td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td></tr>
<tr><td>12.05.2010/2011</td><td></td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td></tr>
<tr><td>19.05.2010/2011</td><td></td><td></td><td></td><td></td><td bgcolor="#c0c0c0"></td></tr>
</table>

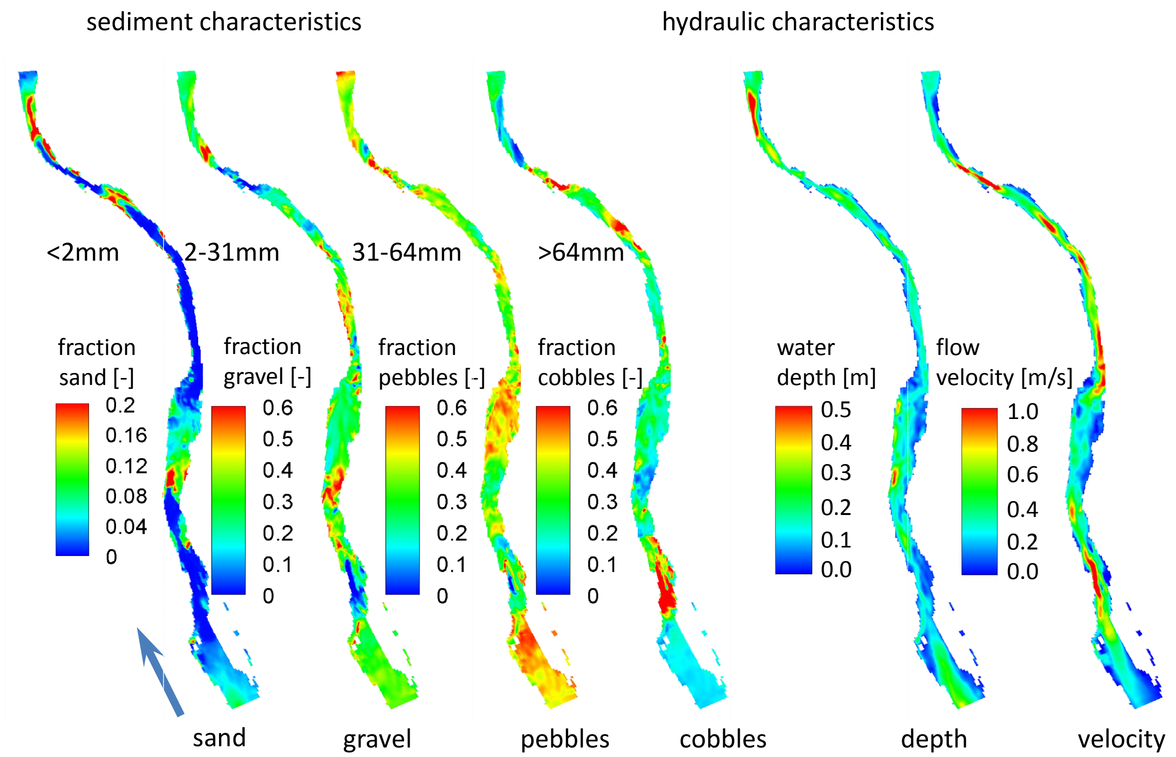
Appendix 8.2: Time-series of input variables to simulate the spawning habitat suitability index (HSI_{spawn}) in spawning period 2009.



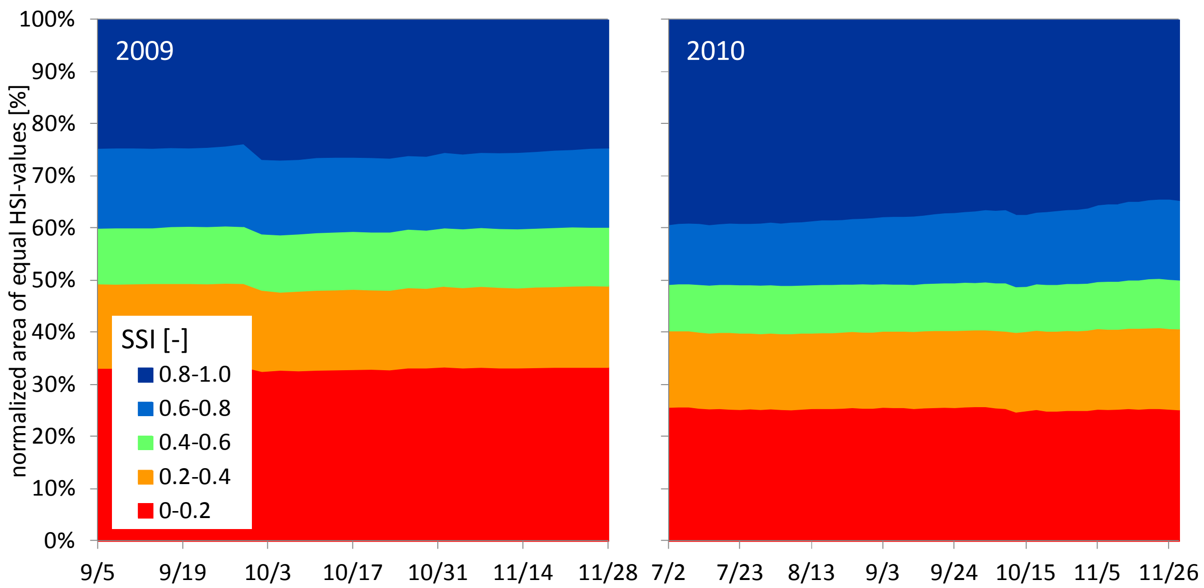
Appendix 8.3: Time-series of input variables to simulate the spawning habitat suitability index (HSI_{spawn} in spawning period 2010.



Appendix 8.4: Visualization of the spatial distribution of input parameter to describe the spawning habitat in the reproduction period 2010/2011.

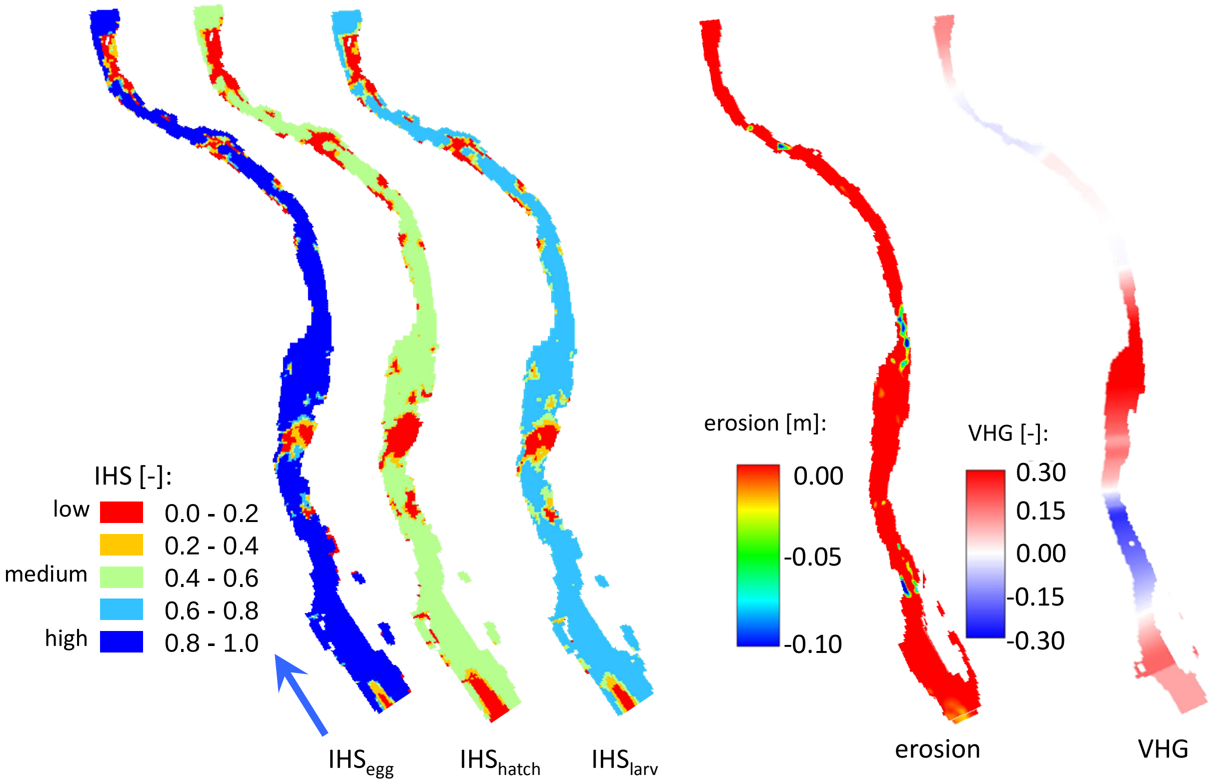


Appendix 8.5: Visualization of areas of equal SSI-values for the spawning periods 2009 and 2010. The time period encompasses the day after artificial flooding until the end of each spawning period.

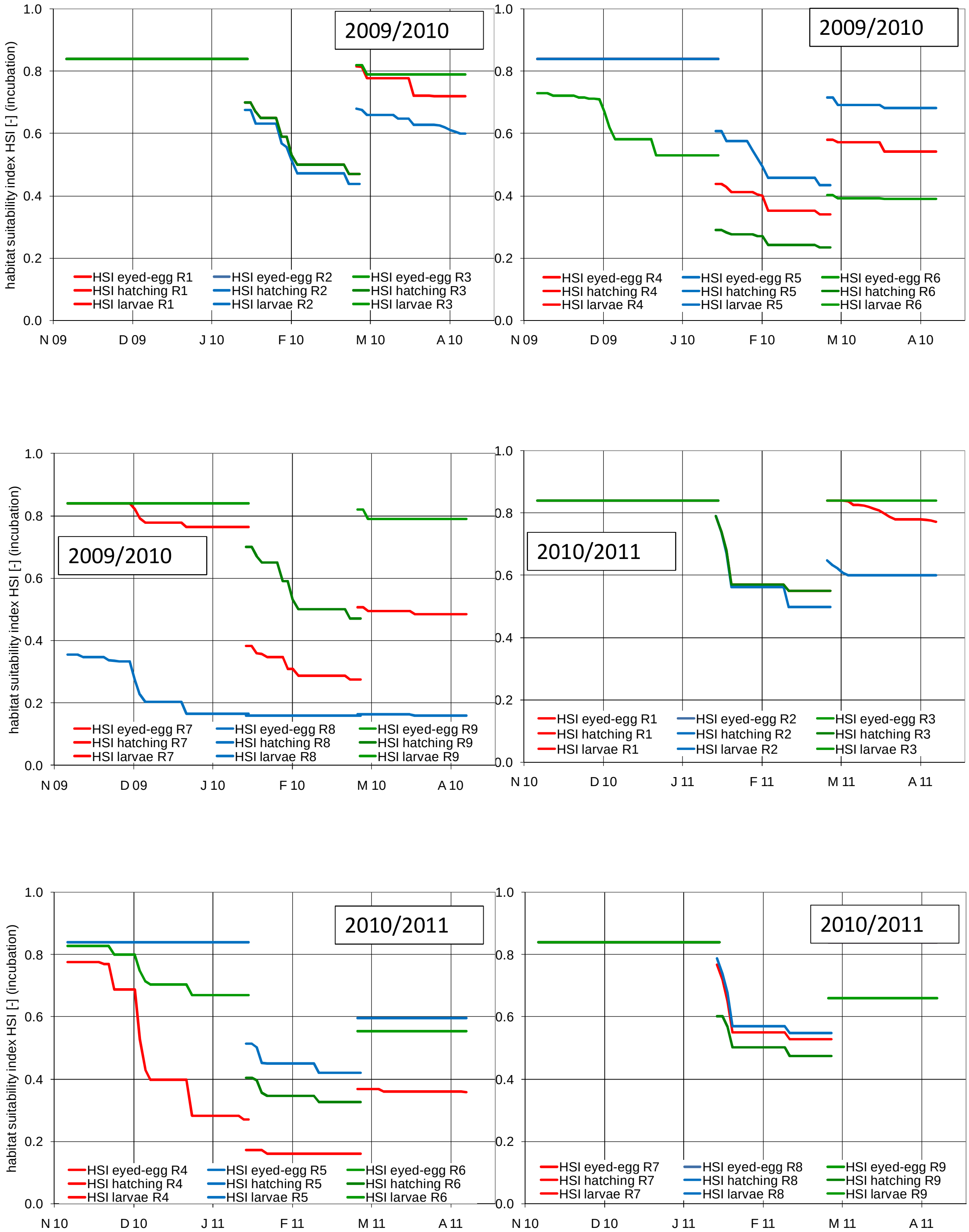


Appendix 9 – simulation of habitat suitability index for life-stages during incubation (HSI_{egg}, HSI_{hatch}, HSI_{larv}) in River Spoel

Appendix 9.1: Visualization of the spatial distribution of input parameter to describe the incubation habitat in the reproduction period 2010/2011.

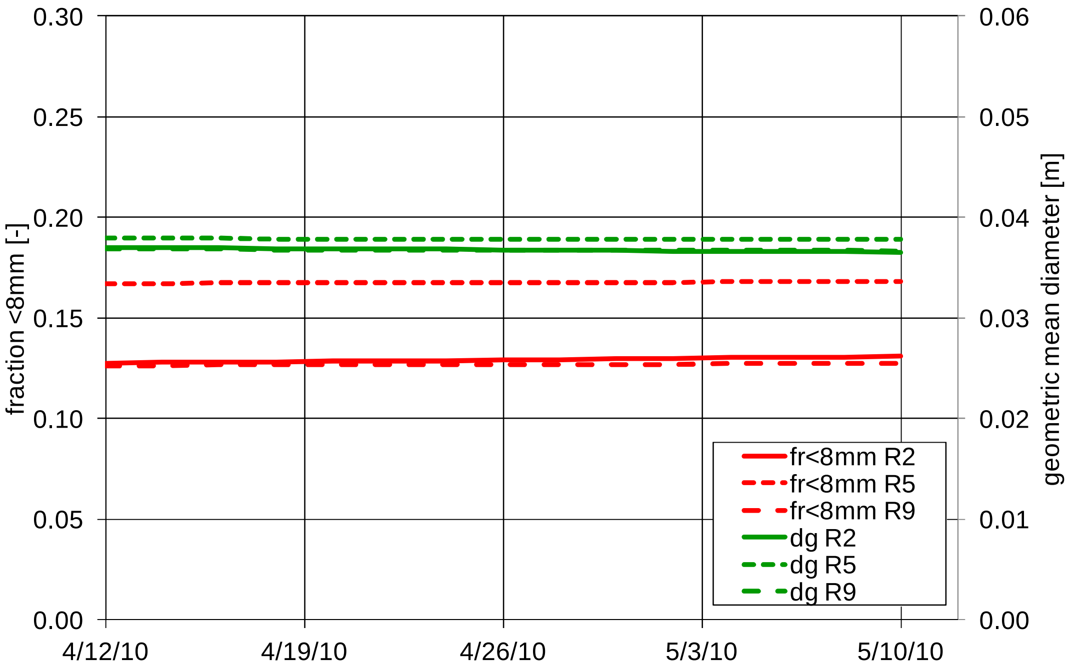


Appendix 9.2: Time-series of habitat suitability indices for the incubational life-stages (HSI_{egg}, HSI_{hatch}, HSI_{larv}) in all artificial redds during both incubation period (2009/2010, 2010/2011).

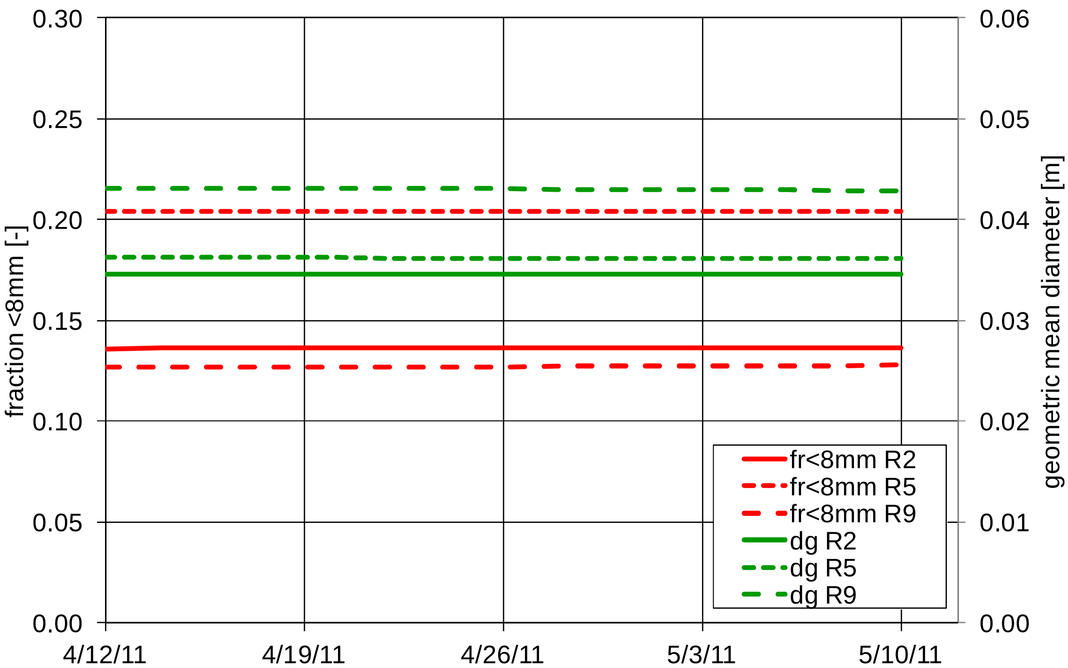


Appendix 10 – simulation of habitat suitability index for the emergence period (HSI_{emerg}) in River Spoel

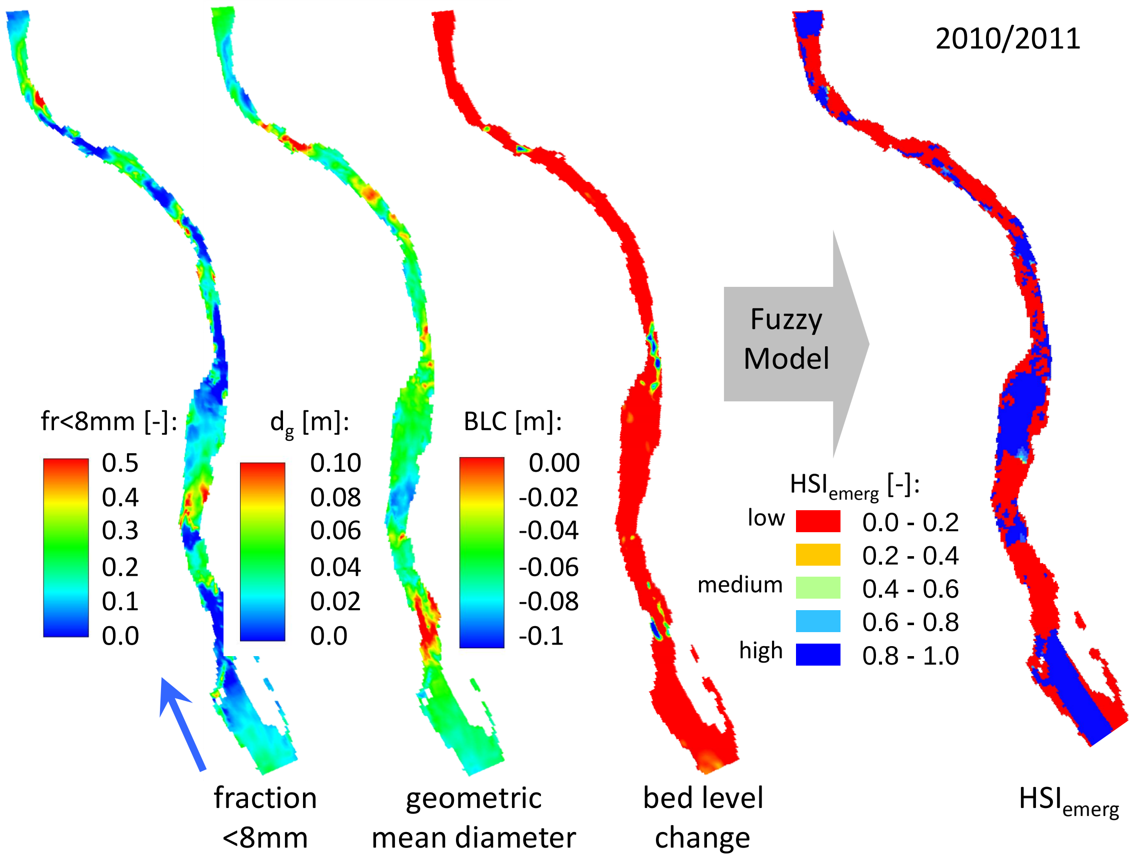
Appendix 10.1: Time-series of input variables to simulate the habitat suitability index for the emergence period (HSI_{emerg}) in the reproduction period 2009/2010. The bed level change is not figured in the diagram below as no bed level changes occurred in the spawning areas.



Appendix 10.2: Time-series of input variables to simulate the habitat suitability index for the emergence period (HSI_{emerg}) in the reproduction period 2010/2011. The bed level change is not figured in the diagram below as no bed level changes occurred in the spawning areas:

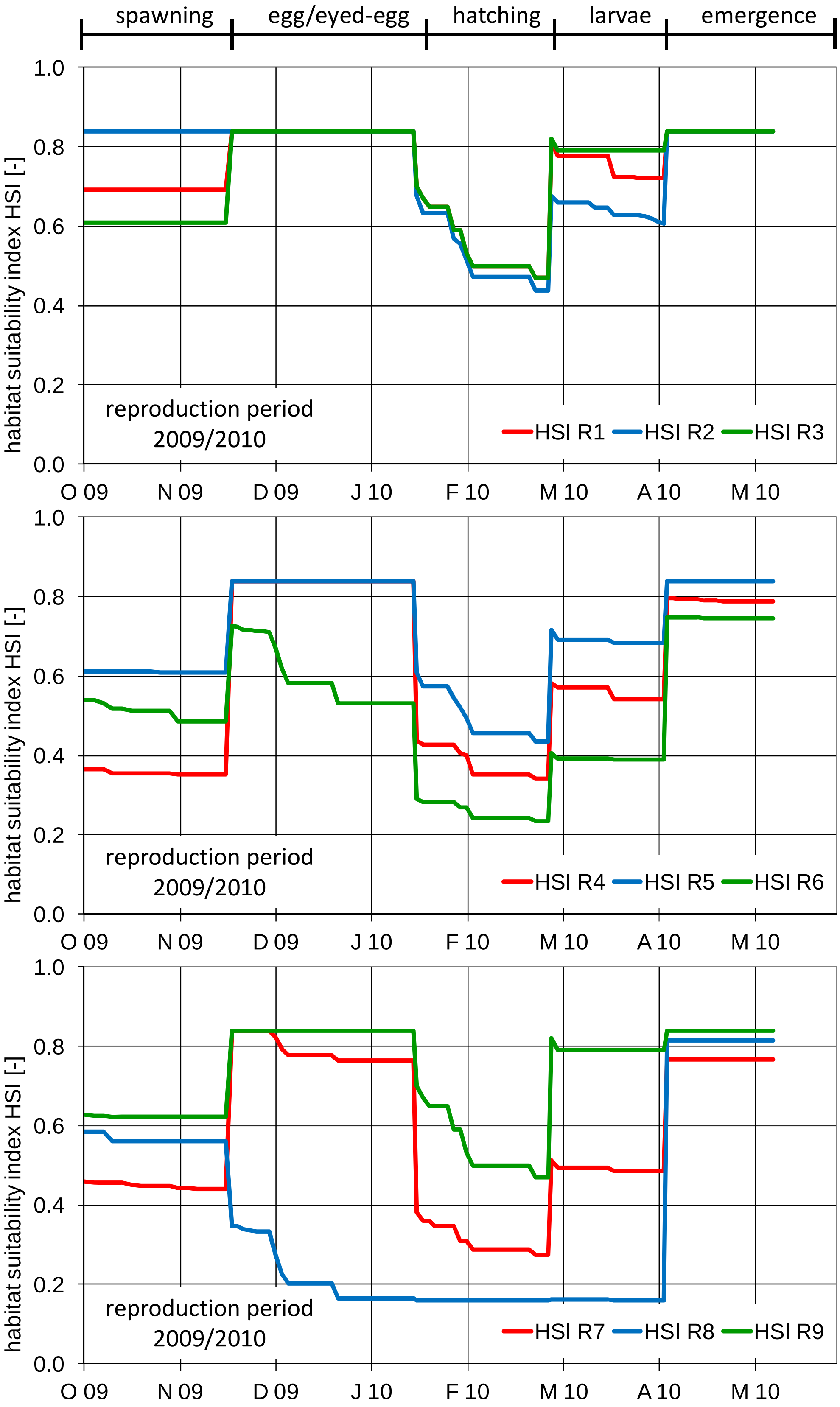


Appendix 10.3: Spatial distribution of in- and output data of the fuzzy-approach to simulate the habitat suitability index for the emergence period (HSI_{emerg}) in the reproduction period 2010/2011:

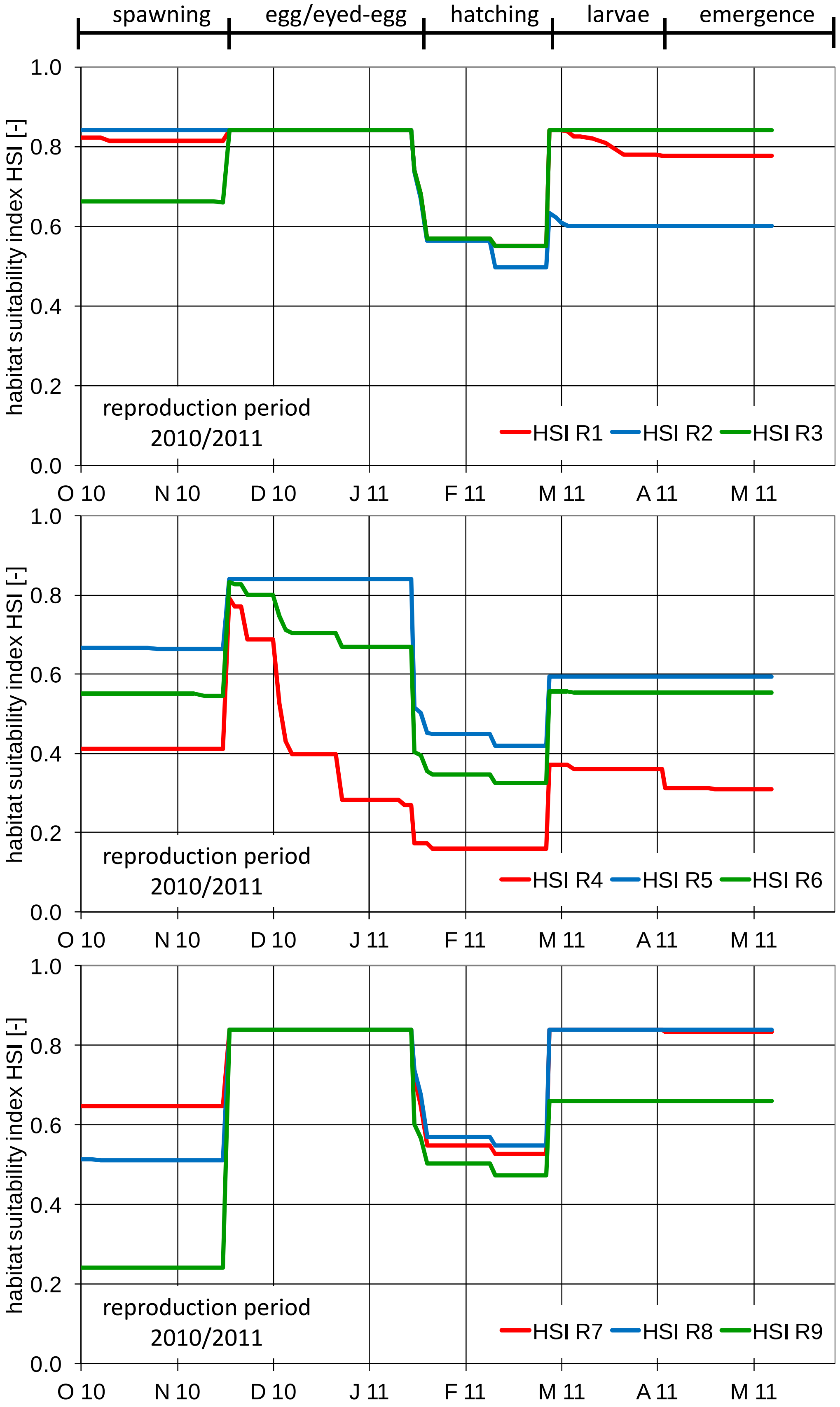


Appendix 11 – simulation of reproduction habitat suitability RHS in River Spoel

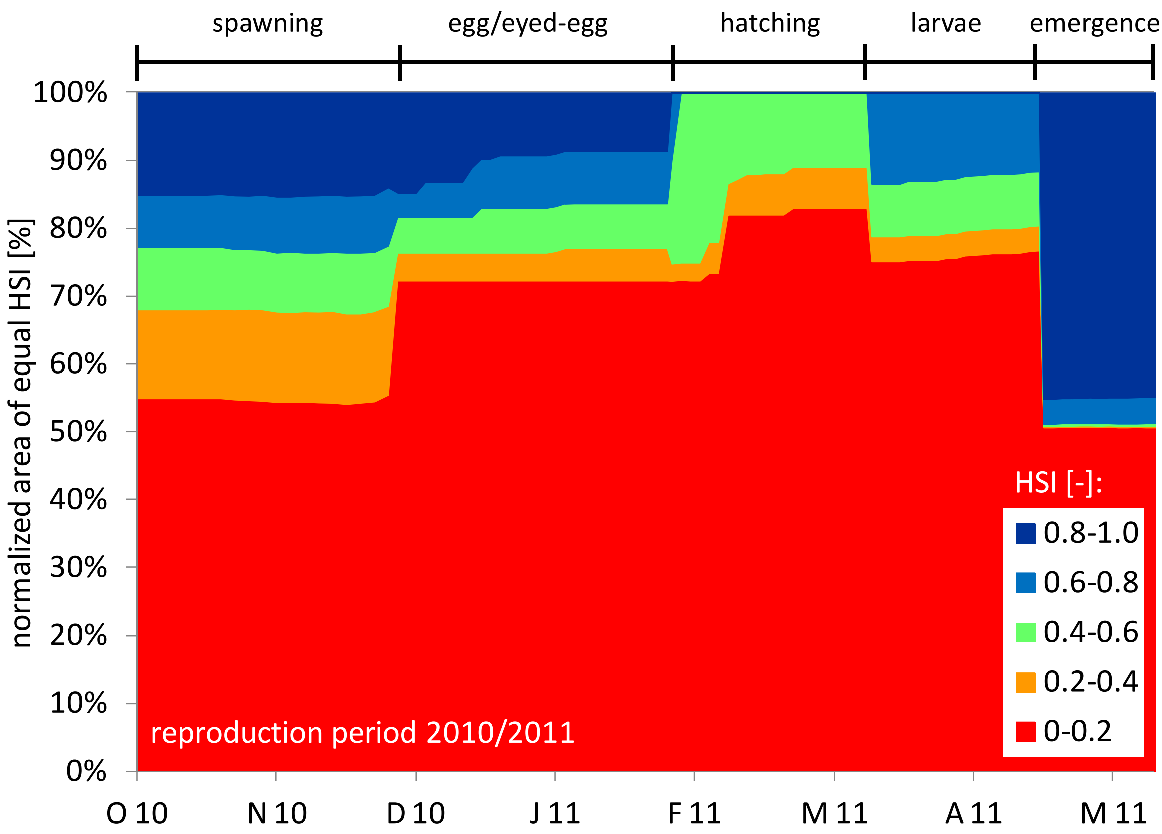
Appendix 11.1: Time-series of HSI-values during the reproduction period 2009/2010.



Appendix 11.2: Time-series of HSI-values during the reproduction period 2010/2011.



Appendix 11.3: Visualisation of areas of equal HSI for all life-stages during the reproduction period 2010/2011.



Lebenslauf

Persönliche Daten

Name:	Markus Noack
Titel:	Diplom-Ingenieur
Addresse:	Emser Straße 83, D-56076 Koblenz
Geburt:	19.02.1980 in Bietigheim-Bissingen
Nationalität:	Deutsch
Familienstatus:	verheiratet, ein Kind
Aktuelle Position:	Wissenschaftlicher Mitarbeiter –Bundesanstalt für Gewässerkunde (BfG)

Beruflicher Werdegang

seit 11/2011	Wissenschaftlicher Mitarbeiter Bundesanstalt für Gewässerkunde (BfG) Referat M3 – Grundwasser, Geologie , Gewässermorphologie
05/2006 – 11/2011	Wissenschaftlicher Mitarbeiter Institut für Wasser- und Umweltsystemmodellierung, Universität Stuttgart Lehrstuhl für Wasserbau und Wassermengenwirtschaft
04/2006 – 12/2006	Projektmanager sje – Schneider & Jorde Ecological Engineering GmbH; Stuttgart
11/2005 – 03/2006	Wissenschaftliche Hilfskraft (geprüft) sje – Schneider & Jorde Ecological Engineering GmbH; Stuttgart
10/2005 – 04/2006	Wissenschaftliche Hilfskraft (geprüft) Institut für Wasser- und Umweltsystemmodellierung, Universität Stuttgart Lehrstuhl für Wasserbau und Wassermengenwirtschaft
02/2005 – 10/2005	Studentische wissenschaftliche Hilfskraft sje – Schneider & Jorde Ecological Engineering GmbH; Stuttgart
10/2003 – 02/2004	Praktikum sje – Schneider & Jorde Ecological Engineering GmbH; Stuttgart
10/2001 – 09/2003	Studentische wissenschaftliche Hilfskraft Institut für Wasser- und Umweltsystemmodellierung, Universität Stuttgart Versuchseinrichtung zur Grundwasser- und Altlastensanierung (VEGAS)

Ausbildung

08/2000 – 10/2005	Studium der Umweltschutztechnik, Universität Stuttgart Vertiefungen: Wasserbau und Wasserwirtschaft, Fließgewässerökologie, Energie und Umwelt Diplomarbeit bei SINTEF, Norwegen
08/1999 – 06/2000	Zivildienst August-Hermann-Werner-Schule Staatliche Schule für Körperbehinderte Markgröningen
09/1990 – 06/1999	Gymnasium Bietigheim-Bissingen, Abitur
09/1986 – 07/1990	Grundschule Bietigheim-Bissingen

Institut für Wasser- und Umweltsystemmodellierung
Universität Stuttgart

Pfaffenwaldring 61
70569 Stuttgart (Vaihingen)
Telefon (0711) 685 - 64717/64749/64752/64679
Telefax (0711) 685 - 67020 o. 64746 o. 64681
E-Mail: iws@iws.uni-stuttgart.de
http://www.iws.uni-stuttgart.de

Verzeichnis der Mitteilungshefte

1 Röhnisch, Arthur: *Die Bemühungen um eine Wasserbauliche Versuchsanstalt an der Technischen Hochschule Stuttgart*, und
Fattah Abouleid, Abdel: *Beitrag zur Berechnung einer in lockeren Sand gerammten, zweifach verankerten Spundwand*, 1963

2 Marotz, Günter: *Beitrag zur Frage der Standfestigkeit von dichten Asphaltbelägen im Großwasserbau*, 1964

3 Gurr, Siegfried: *Beitrag zur Berechnung zusammengesetzter ebener Flächentragwerke unter besonderer Berücksichtigung ebener Stauwände, mit Hilfe von Randwert- und Lastwertmatrizen*, 1965

4 Plica, Peter: *Ein Beitrag zur Anwendung von Schalenkonstruktionen im Stahlwasserbau*, und Petrikat, Kurt: *Möglichkeiten und Grenzen des wasserbaulichen Versuchswesens*, 1966

5 Plate, Erich: *Beitrag zur Bestimmung der Windgeschwindigkeitsverteilung in der durch eine Wand gestörten bodennahen Luftschicht*,
und
Röhnisch, Arthur; Marotz, Günter: *Neue Baustoffe und Bauausführungen für den Schutz der Böschungen und der Sohle von Kanälen, Flüssen und Häfen; Gestehungskosten und jeweilige Vorteile*, sowie Unny, T.E.: *Schwingungsuntersuchungen am Kegelstrahlschieber*, 1967

6 Seiler, Erich: *Die Ermittlung des Anlagenwertes der bundeseigenen Binnenschiffahrtsstraßen und Talsperren und des Anteils der Binnenschiffahrt an diesem Wert*, 1967

7 *Sonderheft anläßlich des 65. Geburtstages von Prof. Arthur Röhnisch mit Beiträgen von* Benk, Dieter; Breitling, J.; Gurr, Siegfried; Haberhauer, Robert; Honekamp, Hermann; Kuz, Klaus Dieter; Marotz, Günter; Mayer-Vorfelder, Hans-Jörg; Miller, Rudolf; Plate, Erich J.; Radomski, Helge; Schwarz, Helmut; Vollmer, Ernst; Wildenhahn, Eberhard; 1967

8 Jumikis, Alfred: *Beitrag zur experimentellen Untersuchung des Wassernachschubs in einem gefrierenden Boden und die Beurteilung der Ergebnisse*, 1968

9 Marotz, Günter: *Technische Grundlagen einer Wasserspeicherung im natürlichen Untergrund*, 1968

10 Radomski, Helge: *Untersuchungen über den Einfluß der Querschnittsform wellenförmiger Spundwände auf die statischen und rammtechnischen Eigenschaften*, 1968

11 Schwarz, Helmut: *Die Grenztragfähigkeit des Baugrundes bei Einwirkung vertikal gezogener Ankerplatten als zweidimensionales Bruchproblem*, 1969

12 Erbel, Klaus: *Ein Beitrag zur Untersuchung der Metamorphose von Mittelgebirgsschneedecken unter besonderer Berücksichtigung eines Verfahrens zur Bestimmung der thermischen Schneequalität*, 1969

13 Westhaus, Karl-Heinz: *Der Strukturwandel in der Binnenschiffahrt und sein Einfluß auf den Ausbau der Binnenschiffskanäle*, 1969

14 Mayer-Vorfelder, Hans-Jörg: *Ein Beitrag zur Berechnung des Erdwiderstandes unter Ansatz der logarithmischen Spirale als Gleitflächenfunktion*, 1970

15 Schulz, Manfred: *Berechnung des räumlichen Erddruckes auf die Wandung kreiszylindrischer Körper*, 1970

16 Mobasseri, Manoutschehr: *Die Rippenstützmauer. Konstruktion und Grenzen ihrer Standsicherheit*, 1970

17 Benk, Dieter: *Ein Beitrag zum Betrieb und zur Bemessung von Hochwasserrückhaltebecken*, 1970

18 Gàl, Attila: *Bestimmung der mitschwingenden Wassermasse bei überströmten Fischbauchklappen mit kreiszylindrischem Staublech*, 1971, vergriffen

19 Kuz, Klaus Dieter: *Ein Beitrag zur Frage des Einsetzens von Kavitationserscheinungen in einer Düsenströmung bei Berücksichtigung der im Wasser gelösten Gase*, 1971, vergriffen

20 Schaak, Hartmut: *Verteilleitungen von Wasserkraftanlagen*, 1971

21 *Sonderheft zur Eröffnung der neuen Versuchsanstalt des Instituts für Wasserbau der Universität Stuttgart mit Beiträgen von* Brombach, Hansjörg; Dirksen, Wolfram; Gàl, Attila; Gerlach, Reinhard; Giesecke, Jürgen; Holthoff, Franz-Josef; Kuz, Klaus Dieter; Marotz, Günter; Minor, Hans-Erwin; Petrikat, Kurt; Röhnisch, Arthur; Rueff, Helge; Schwarz, Helmut; Vollmer, Ernst; Wildenhahn, Eberhard; 1972

22 Wang, Chung-su: *Ein Beitrag zur Berechnung der Schwingungen an Kegelstrahlschiebern*, 1972

23 Mayer-Vorfelder, Hans-Jörg: *Erdwiderstandsbeiwerte nach dem Ohde-Variationsverfahren*, 1972

24 Minor, Hans-Erwin: *Beitrag zur Bestimmung der Schwingungsanfachungsfunktionen überströmter Stauklappen*, 1972, vergriffen

25 Brombach, Hansjörg: *Untersuchung strömungsmechanischer Elemente (Fluidik) und die Möglichkeit der Anwendung von Wirbelkammerelementen im Wasserbau*, 1972, vergriffen

26 Wildenhahn, Eberhard: *Beitrag zur Berechnung von Horizontalfilterbrunnen*, 1972

27 Steinlein, Helmut: *Die Eliminierung der Schwebstoffe aus Flußwasser zum Zweck der unterirdischen Wasserspeicherung, gezeigt am Beispiel der Iller*, 1972

28 Holthoff, Franz Josef: *Die Überwindung großer Hubhöhen in der Binnenschiffahrt durch Schwimmerhebewerke*, 1973

29 Röder, Karl: *Einwirkungen aus Baugrundbewegungen auf trog- und kastenförmige Konstruktionen des Wasser- und Tunnelbaues*, 1973

30 Kretschmer, Heinz: *Die Bemessung von Bogenstaumauern in Abhängigkeit von der Talform*, 1973

31 Honekamp, Hermann: *Beitrag zur Berechnung der Montage von Unterwasserpipelines*, 1973

32 Giesecke, Jürgen: *Die Wirbelkammertriode als neuartiges Steuerorgan im Wasserbau*, und Brombach, Hansjörg: *Entwicklung, Bauformen, Wirkungsweise und Steuereigenschaften von Wirbelkammerverstärkern*, 1974

33 Rueff, Helge: *Untersuchung der schwingungserregenden Kräfte an zwei hintereinander angeordneten Tiefschützen unter besonderer Berücksichtigung von Kavitation*, 1974

34 Röhnisch, Arthur: *Einpreßversuche mit Zementmörtel für Spannbeton - Vergleich der Ergebnisse von Modellversuchen mit Ausführungen in Hüllwellrohren*, 1975

35 *Sonderheft anläßlich des 65. Geburtstages von Prof. Dr.-Ing. Kurt Petrikat mit Beiträgen von*: Brombach, Hansjörg; Erbel, Klaus; Flinspach, Dieter; Fischer jr., Richard; Gàl, Attila; Gerlach, Reinhard; Giesecke, Jürgen; Haberhauer, Robert; Hafner Edzard; Hausenblas, Bernhard; Horlacher, Hans-Burkhard; Hutarew, Andreas; Knoll, Manfred; Krummet, Ralph; Marotz, Günter; Merkle, Theodor; Miller, Christoph; Minor, Hans-Erwin; Neumayer, Hans; Rao, Syamala; Rath, Paul; Rueff, Helge; Ruppert, Jürgen; Schwarz, Wolfgang; Topal-Gökceli, Mehmet; Vollmer, Ernst; Wang, Chung-su; Weber, Hans-Georg; 1975

36 Berger, Jochum: *Beitrag zur Berechnung des Spannungszustandes in rotationssymmetrisch belasteten Kugelschalen veränderlicher Wandstärke unter Gas- und Flüssigkeitsdruck durch Integration schwach singulärer Differentialgleichungen*, 1975

37 Dirksen, Wolfram: *Berechnung instationärer Abflußvorgänge in gestauten Gerinnen mittels Differenzenverfahren und die Anwendung auf Hochwasserrückhaltebecken*, 1976

38 Horlacher, Hans-Burkhard: *Berechnung instationärer Temperatur- und Wärmespannungsfelder in langen mehrschichtigen Hohlzylindern*, 1976

39 Hafner, Edzard: *Untersuchung der hydrodynamischen Kräfte auf Baukörper im Tiefwasserbereich des Meeres*, 1977, ISBN 3-921694-39-6

40 Ruppert, Jürgen: *Über den Axialwirbelkammerverstärker für den Einsatz im Wasserbau*, 1977, ISBN 3-921694-40-X

41 Hutarew, Andreas: *Beitrag zur Beeinflußbarkeit des Sauerstoffgehalts in Fließgewässern an Abstürzen und Wehren*, 1977, ISBN 3-921694-41-8, vergriffen

42 Miller, Christoph: *Ein Beitrag zur Bestimmung der schwingungserregenden Kräfte an unterströmten Wehren*, 1977, ISBN 3-921694-42-6

43 Schwarz, Wolfgang: *Druckstoßberechnung unter Berücksichtigung der Radial- und Längsverschiebungen der Rohrwandung*, 1978, ISBN 3-921694-43-4

44 Kinzelbach, Wolfgang: *Numerische Untersuchungen über den optimalen Einsatz variabler Kühlsysteme einer Kraftwerkskette am Beispiel Oberrhein*, 1978, ISBN 3-921694-44-2

45 Barczewski, Baldur: *Neue Meßmethoden für Wasser-Luftgemische und deren Anwendung auf zweiphasige Auftriebsstrahlen*, 1979, ISBN 3-921694-45-0

46 Neumayer, Hans: *Untersuchung der Strömungsvorgänge in radialen Wirbelkammerverstärkern*, 1979, ISBN 3-921694-46-9

47 Elalfy, Youssef-Elhassan: *Untersuchung der Strömungsvorgänge in Wirbelkammerdioden und -drosseln*, 1979, ISBN 3-921694-47-7

48 Brombach, Hansjörg: *Automatisierung der Bewirtschaftung von Wasserspeichern*, 1981, ISBN 3-921694-48-5

49 Geldner, Peter: *Deterministische und stochastische Methoden zur Bestimmung der Selbstdichtung von Gewässern*, 1981, ISBN 3-921694-49-3, vergriffen

50 Mehlhorn, Hans: *Temperaturveränderungen im Grundwasser durch Brauchwassereinleitungen*, 1982, ISBN 3-921694-50-7, vergriffen

51 Hafner, Edzard: *Rohrleitungen und Behälter im Meer*, 1983, ISBN 3-921694-51-5

52 Rinnert, Bernd: *Hydrodynamische Dispersion in porösen Medien: Einfluß von Dichteunterschieden auf die Vertikalvermischung in horizontaler Strömung*, 1983, ISBN 3-921694-52-3, vergriffen

53 Lindner, Wulf: *Steuerung von Grundwasserentnahmen unter Einhaltung ökologischer Kriterien*, 1983, ISBN 3-921694-53-1, vergriffen

54 Herr, Michael; Herzer, Jörg; Kinzelbach, Wolfgang; Kobus, Helmut; Rinnert, Bernd: *Methoden zur rechnerischen Erfassung und hydraulischen Sanierung von Grundwasserkontaminationen*, 1983, ISBN 3-921694-54-X

55 Schmitt, Paul: *Wege zur Automatisierung der Niederschlagsermittlung*, 1984, ISBN 3-921694-55-8, vergriffen

56 Müller, Peter: *Transport und selektive Sedimentation von Schwebstoffen bei gestautem Abfluß*, 1985, ISBN 3-921694-56-6

57 El-Qawasmeh, Fuad: *Möglichkeiten und Grenzen der Tropfbewässerung unter besonderer Berücksichtigung der Verstopfungsanfälligkeit der Tropfelemente*, 1985, ISBN 3-921694-57-4, vergriffen

58 Kirchenbaur, Klaus: *Mikroprozessorgesteuerte Erfassung instationärer Druckfelder am Beispiel seegangsbelasteter Baukörper*, 1985, ISBN 3-921694-58-2

59 Kobus, Helmut (Hrsg.): *Modellierung des großräumigen Wärme- und Schadstofftransports im Grundwasser*, Tätigkeitsbericht 1984/85 (DFG-Forschergruppe an den Universitäten Hohenheim, Karlsruhe und Stuttgart), 1985, ISBN 3-921694-59-0, vergriffen

60 Spitz, Karlheinz: *Dispersion in porösen Medien: Einfluß von Inhomogenitäten und Dichteunterschieden*, 1985, ISBN 3-921694-60-4, vergriffen

61 Kobus, Helmut: *An Introduction to Air-Water Flows in Hydraulics*, 1985, ISBN 3-921694-61-2

62 Kaleris, Vassilios: *Erfassung des Austausches von Oberflächen- und Grundwasser in horizontalebenen Grundwassermodellen*, 1986, ISBN 3-921694-62-0

63 Herr, Michael: *Grundlagen der hydraulischen Sanierung verunreinigter Porengrundwasserleiter*, 1987, ISBN 3-921694-63-9

64 Marx, Walter: *Berechnung von Temperatur und Spannung in Massenbeton infolge Hydratation*, 1987, ISBN 3-921694-64-7

65 Koschitzky, Hans-Peter: *Dimensionierungskonzept für Sohlbelüfter in Schußrinnen zur Vermeidung von Kavitationsschäden*, 1987, ISBN 3-921694-65-5

66 Kobus, Helmut (Hrsg.): *Modellierung des großräumigen Wärme- und Schadstofftransports im Grundwasser*, Tätigkeitsbericht 1986/87 (DFG-Forschergruppe an den Universitäten Hohenheim, Karlsruhe und Stuttgart) 1987, ISBN 3-921694-66-3

67 Söll, Thomas: *Berechnungsverfahren zur Abschätzung anthropogener Temperaturanomalien im Grundwasser*, 1988, ISBN 3-921694-67-1

68 Dittrich, Andreas; Westrich, Bernd: *Bodenseeufererosion, Bestandsaufnahme und Bewertung*, 1988, ISBN 3-921694-68-X, vergriffen

69 Huwe, Bernd; van der Ploeg, Rienk R.: *Modelle zur Simulation des Stickstoffhaushaltes von Standorten mit unterschiedlicher landwirtschaftlicher Nutzung*, 1988, ISBN 3-921694-69-8, vergriffen

70 Stephan, Karl: *Integration elliptischer Funktionen*, 1988, ISBN 3-921694-70-1

71 Kobus, Helmut; Zilliox, Lothaire (Hrsg.): *Nitratbelastung des Grundwassers, Auswirkungen der Landwirtschaft auf die Grundwasser- und Rohwasserbeschaffenheit und Maßnahmen zum Schutz des Grundwassers*. Vorträge des deutsch-französischen Kolloquiums am 6. Oktober 1988, Universitäten Stuttgart und Louis Pasteur Strasbourg (Vorträge in deutsch oder französisch, Kurzfassungen zweisprachig), 1988, ISBN 3-921694-71-X

72 Soyeaux, Renald: *Unterströmung von Stauanlagen auf klüftigem Untergrund unter Berücksichtigung laminarer und turbulenter Fließzustände*,1991, ISBN 3-921694-72-8

73 Kohane, Roberto: *Berechnungsmethoden für Hochwasserabfluß in Fließgewässern mit überströmten Vorländern*, 1991, ISBN 3-921694-73-6

74 Hassinger, Reinhard: *Beitrag zur Hydraulik und Bemessung von Blocksteinrampen in flexibler Bauweise*, 1991, ISBN 3-921694-74-4, vergriffen

75 Schäfer, Gerhard: *Einfluß von Schichtenstrukturen und lokalen Einlagerungen auf die Längsdispersion in Porengrundwasserleitern*, 1991, ISBN 3-921694-75-2

76 Giesecke, Jürgen: *Vorträge, Wasserwirtschaft in stark besiedelten Regionen; Umweltforschung mit Schwerpunkt Wasserwirtschaft*, 1991, ISBN 3-921694-76-0

77 Huwe, Bernd: *Deterministische und stochastische Ansätze zur Modellierung des Stickstoffhaushalts landwirtschaftlich genutzter Flächen auf unterschiedlichem Skalenniveau*, 1992, ISBN 3-921694-77-9, vergriffen

78 Rommel, Michael: *Verwendung von Kluftdaten zur realitätsnahen Generierung von Kluftnetzen mit anschließender laminar-turbulenter Strömungsberechnung*, 1993, ISBN 3-92 1694-78-7

79 Marschall, Paul: *Die Ermittlung lokaler Stofffrachten im Grundwasser mit Hilfe von Einbohrloch-Meßverfahren*, 1993, ISBN 3-921694-79-5, vergriffen

80 Ptak, Thomas: *Stofftransport in heterogenen Porenaquiferen: Felduntersuchungen und stochastische Modellierung*, 1993, ISBN 3-921694-80-9, vergriffen

81 Haakh, Frieder: *Transientes Strömungsverhalten in Wirbelkammern,* 1993, ISBN 3-921694-81-7

82 Kobus, Helmut; Cirpka, Olaf; Barczewski, Baldur; Koschitzky, Hans-Peter: *Versucheinrichtung zur Grundwasser und Altlastensanierung VEGAS, Konzeption und Programmrahmen*, 1993, ISBN 3-921694-82-5

83 Zang, Weidong: *Optimaler Echtzeit-Betrieb eines Speichers mit aktueller Abflußregenerierung*, 1994, ISBN 3-921694-83-3, vergriffen

84 Franke, Hans-Jörg: *Stochastische Modellierung eines flächenhaften Stoffeintrages und Transports in Grundwasser am Beispiel der Pflanzenschutzmittelproblematik*, 1995, ISBN 3-921694-84-1

85 Lang, Ulrich: *Simulation regionaler Strömungs- und Transportvorgänge in Karstaquiferen mit Hilfe des Doppelkontinuum-Ansatzes: Methodenentwicklung und Parameteridentifikation*, 1995, ISBN 3-921694-85-X, vergriffen

86 Helmig, Rainer: *Einführung in die Numerischen Methoden der Hydromechanik*, 1996, ISBN 3-921694-86-8, vergriffen

87 Cirpka, Olaf: *CONTRACT: A Numerical Tool for Contaminant Transport and Chemical Transformations - Theory and Program Documentation -*, 1996, ISBN 3-921694-87-6

88 Haberlandt, Uwe: *Stochastische Synthese und Regionalisierung des Niederschlages für Schmutzfrachtberechnungen*, 1996, ISBN 3-921694-88-4

89 Croisé, Jean: *Extraktion von flüchtigen Chemikalien aus natürlichen Lockergesteinen mittels erzwungener Luftströmung*, 1996, ISBN 3-921694-89-2, vergriffen

90 Jorde, Klaus: *Ökologisch begründete, dynamische Mindestwasserregelungen bei Ausleitungskraftwerken*, 1997, ISBN 3-921694-90-6, vergriffen

91 Helmig, Rainer: *Gekoppelte Strömungs- und Transportprozesse im Untergrund - Ein Beitrag zur Hydrosystemmodellierung-*, 1998, ISBN 3-921694-91-4, vergriffen

92 Emmert, Martin: *Numerische Modellierung nichtisothermer Gas-Wasser Systeme in porösen Medien,* 1997, ISBN 3-921694-92-2

93 Kern, Ulrich: *Transport von Schweb- und Schadstoffen in staugeregelten Fließgewässern am Beispiel des Neckars*, 1997, ISBN 3-921694-93-0, vergriffen

94 Förster, Georg: *Druckstoßdämpfung durch große Luftblasen in Hochpunkten von Rohrleitungen 1997*, ISBN 3-921694-94-9

95 Cirpka, Olaf: *Numerische Methoden zur Simulation des reaktiven Mehrkomponententransports im Grundwasser*, 1997, ISBN 3-921694-95-7, vergriffen

96 Färber, Arne: *Wärmetransport in der ungesättigten Bodenzone: Entwicklung einer thermischen In-situ-Sanierungstechnologie*, 1997, ISBN 3-921694-96-5

97 Betz, Christoph: *Wasserdampfdestillation von Schadstoffen im porösen Medium: Entwicklung einer thermischen In-situ-Sanierungstechnologie*, 1998, ISBN 3-921694-97-3

98 Xu, Yichun: *Numerical Modeling of Suspended Sediment Transport in Rivers*, 1998, ISBN 3-921694-98-1, vergriffen

99 Wüst, Wolfgang: *Geochemische Untersuchungen zur Sanierung CKW-kontaminierter Aquifere mit Fe(0)-Reaktionswänden,* 2000, ISBN 3-933761-02-2

100 Sheta, Hussam: *Simulation von Mehrphasenvorgängen in porösen Medien unter Einbeziehung von Hysterese-Effekten*, 2000, ISBN 3-933761-03-4

101 Ayros, Edwin: *Regionalisierung extremer Abflüsse auf der Grundlage statistischer Verfahren*, 2000, ISBN 3-933761-04-2, vergriffen

102 Huber, Ralf: *Compositional Multiphase Flow and Transport in Heterogeneous Porous Media*, 2000, ISBN 3-933761-05-0

103 Braun, Christopherus: *Ein Upscaling-Verfahren für Mehrphasenströmungen in porösen Medien*, 2000, ISBN 3-933761-06-9

104 Hofmann, Bernd: *Entwicklung eines rechnergestützten Managementsystems zur Beurteilung von Grundwasserschadensfällen*, 2000, ISBN 3-933761-07-7

105 Class, Holger: *Theorie und numerische Modellierung nichtisothermer Mehrphasenprozesse in NAPL-kontaminierten porösen Medien,* 2001, ISBN 3-933761-08-5

106 Schmidt, Reinhard: *Wasserdampf- und Heißluftinjektion zur thermischen Sanierung kontaminierter Standorte*, 2001, ISBN 3-933761-09-3

107 Josef, Reinhold:, *Schadstoffextraktion mit hydraulischen Sanierungsverfahren unter Anwendung von grenzflächenaktiven Stoffen*, 2001, ISBN 3-933761-10-7

108 Schneider, Matthias: *Habitat- und Abflussmodellierung für Fließgewässer mit unscharfen Berechnungsansätzen*, 2001, ISBN 3-933761-11-5

109 Rathgeb, Andreas: *Hydrodynamische Bemessungsgrundlagen für Lockerdeckwerke an überströmbaren Erddämmen*, 2001, ISBN 3-933761-12-3

110 Lang, Stefan: *Parallele numerische Simulation instätionärer Probleme mit adaptiven Methoden auf unstrukturierten Gittern*, 2001, ISBN 3-933761-13-1

111 Appt, Jochen; Stumpp Simone: *Die Bodensee-Messkampagne 2001, IWS/CWR Lake Constance Measurement Program 2001*, 2002, ISBN 3-933761-14-X

112 Heimerl, Stephan: *Systematische Beurteilung von Wasserkraftprojekten,* 2002, ISBN 3-933761-15-8, vergriffen

113 Iqbal, Amin: *On the Management and Salinity Control of Drip Irrigation,* 2002, ISBN 3-933761-16-6

114 Silberhorn-Hemminger, Annette: *Modellierung von Kluftaquifersystemen: Geostatistische Analyse und deterministisch-stochastische Kluftgenerierung,* 2002, ISBN 3-933761-17-4

115 Winkler, Angela: *Prozesse des Wärme- und Stofftransports bei der In-situ-Sanierung mit festen Wärmequellen,* 2003, ISBN 3-933761-18-2

116 Marx, Walter: *Wasserkraft, Bewässerung, Umwelt - Planungs- und Bewertungsschwerpunkte der Wasserbewirtschaftung,* 2003, ISBN 3-933761-19-0

117 Hinkelmann, Reinhard: *Efficient Numerical Methods and Information-Processing Techniques in Environment Water,* 2003, ISBN 3-933761-20-4

118 Samaniego-Eguiguren, Luis Eduardo: *Hydrological Consequences of Land Use / Land Cover and Climatic Changes in Mesoscale Catchments*, 2003, ISBN 3-933761-21-2

119 Neunhäuserer, Lina: *Diskretisierungsansätze zur Modellierung von Strömungs- und Transportprozessen in geklüftet-porösen Medien*, 2003, ISBN 3-933761-22-0

120 Paul, Maren: *Simulation of Two-Phase Flow in Heterogeneous Poros Media with Adaptive Methods*, 2003, ISBN 3-933761-23-9

121 Ehret, Uwe: *Rainfall and Flood Nowcasting in Small Catchments using Weather Radar*, 2003, ISBN 3-933761-24-7

122 Haag, Ingo: *Der Sauerstoffhaushalt staugeregelter Flüsse am Beispiel des Neckars - Analysen, Experimente, Simulationen -,* 2003, ISBN 3-933761-25-5

123 Appt, Jochen: *Analysis of Basin-Scale Internal Waves in Upper Lake Constance,* 2003, ISBN 3-933761-26-3

124 Hrsg.: Schrenk, Volker; Batereau, Katrin; Barczewski, Baldur; Weber, Karolin und Koschitzky, Hans-Peter: *Symposium Ressource Fläche und VEGAS - Statuskolloquium 2003, 30. September und 1. Oktober 2003,* 2003, ISBN 3-933761-27-1

125 Omar Khalil Ouda: *Optimisation of Agricultural Water Use: A Decision Support System for the Gaza Strip,* 2003, ISBN 3-933761-28-0

126 Batereau, Katrin: *Sensorbasierte Bodenluftmessung zur Vor-Ort-Erkundung von Schadensherden im Untergrund*, 2004, ISBN 3-933761-29-8

127 Witt, Oliver: *Erosionsstabilität von Gewässersedimenten mit Auswirkung auf den Stofftransport bei Hochwasser am Beispiel ausgewählter Stauhaltungen des Oberrheins*, 2004, ISBN 3-933761-30-1

128 Jakobs, Hartmut: *Simulation nicht-isothermer Gas-Wasser-Prozesse in komplexen Kluft-Matrix-Systemen*, 2004, ISBN 3-933761-31-X

129 Li, Chen-Chien: *Deterministisch-stochastisches Berechnungskonzept zur Beurteilung der Auswirkungen erosiver Hochwasserereignisse in Flussstauhaltungen,* 2004, ISBN 3-933761-32-8

130 Reichenberger, Volker; Helmig, Rainer; Jakobs, Hartmut; Bastian, Peter; Niessner, Jennifer: *Complex Gas-Water Processes in Discrete Fracture-Matrix Systems: Upscaling, Mass-Conservative Discretization and Efficient Multilevel Solution,* 2004, ISBN 3-933761-33-6

131 Hrsg.: Barczewski, Baldur; Koschitzky, Hans-Peter; Weber, Karolin; Wege, Ralf: *VEGAS - Statuskolloquium 2004,* Tagungsband zur Veranstaltung am 05. Oktober 2004 an der Universität Stuttgart, Campus Stuttgart-Vaihingen, 2004, ISBN 3-933761-34-4

132 Asie, Kemal Jabir: *Finite Volume Models for Multiphase Multicomponent Flow through Porous Media*. 2005, ISBN 3-933761-35-2

133 Jacoub, George: *Development of a 2-D Numerical Module for Particulate Contaminant Transport in Flood Retention Reservoirs and Impounded Rivers,* 2004, ISBN 3-933761-36-0

134 Nowak, Wolfgang: *Geostatistical Methods for the Identification of Flow and Transport Parameters in the Subsurface,* 2005, ISBN 3-933761-37-9

135 Süß, Mia: *Analysis of the influence of structures and boundaries on flow and transport processes in fractured porous media*, 2005, ISBN 3-933761-38-7

136 Jose, Surabhin Chackiath: *Experimental Investigations on Longitudinal Dispersive Mixing in Heterogeneous Aquifers,* 2005, ISBN: 3-933761-39-5

137 Filiz, Fulya: *Linking Large-Scale Meteorological Conditions to Floods in Mesoscale Catchments,* 2005, ISBN 3-933761-40-9

138 Qin, Minghao: *Wirklichkeitsnahe und recheneffiziente Ermittlung von Temperatur und Spannungen bei großen RCC-Staumauern*, 2005, ISBN 3-933761-41-7

139 Kobayashi, Kenichiro: *Optimization Methods for Multiphase Systems in the Subsurface - Application to Methane Migration in Coal Mining Areas*, 2005, ISBN 3-933761-42-5

140 Rahman, Md. Arifur: *Experimental Investigations on Transverse Dispersive Mixing in Heterogeneous Porous Media,* 2005, ISBN 3-933761-43-3

141 Schrenk, Volker: *Ökobilanzen zur Bewertung von Altlastensanierungsmaßnahmen,* 2005, ISBN 3-933761-44-1

142 Hundecha, Hirpa Yeshewatesfa: *Regionalization of Parameters of a Conceptual Rainfall-Runoff Model*, 2005, ISBN: 3-933761-45-X

143 Wege, Ralf: *Untersuchungs- und Überwachungsmethoden für die Beurteilung natürlicher Selbstreinigungsprozesse im Grundwasser,* 2005, ISBN 3-933761-46-8

144 Breiting, Thomas: *Techniken und Methoden der Hydroinformatik - Modellierung von komplexen Hydrosystemen im Untergrund*, 2006, 3-933761-47-6

145 Hrsg.: Braun, Jürgen; Koschitzky, Hans-Peter; Müller, Martin: *Ressource Untergrund: 10 Jahre VEGAS: Forschung und Technologieentwicklung zum Schutz von Grundwasser und Boden,* Tagungsband zur Veranstaltung am 28. und 29. September 2005 an der Universität Stuttgart, Campus Stuttgart-Vaihingen, 2005, ISBN 3-933761-48-4

146 Rojanschi, Vlad: *Abflusskonzentration in mesoskaligen Einzugsgebieten unter Berücksichtigung des Sickerraumes,* 2006, ISBN 3-933761-49-2

147 Winkler, Nina Simone: *Optimierung der Steuerung von Hochwasserrückhaltebecken-systemen,* 2006, ISBN 3-933761-50-6

148 Wolf, Jens: *Räumlich differenzierte Modellierung der Grundwasserströmung alluvialer Aquifere für mesoskalige Einzugsgebiete*, 2006, ISBN: 3-933761-51-4

149 Kohler, Beate: *Externe Effekte der Laufwasserkraftnutzung*, 2006, ISBN 3-933761-52-2

150 Hrsg.: Braun, Jürgen; Koschitzky, Hans-Peter; Stuhrmann, Matthias: *VEGAS-Statuskolloquium 2006,* Tagungsband zur Veranstaltung am 28. September 2006 an der Universität Stuttgart, Campus Stuttgart-Vaihingen, 2006, ISBN 3-933761-53-0

151 Niessner, Jennifer: *Multi-Scale Modeling of Multi-Phase - Multi-Component Processes in Heterogeneous Porous Media*, 2006, ISBN 3-933761-54-9

152 Fischer, Markus: *Beanspruchung eingeerdeter Rohrleitungen infolge Austrocknung bindiger Böden,* 2006, ISBN 3-933761-55-7

153 Schneck, Alexander: *Optimierung der Grundwasserbewirtschaftung unter Berücksichtigung der Belange der Wasserversorgung, der Landwirtschaft und des Naturschutzes*, 2006, ISBN 3-933761-56-5

154 Das, Tapash: *The Impact of Spatial Variability of Precipitation on the Predictive Uncertainty of Hydrological Models,* 2006, ISBN 3-933761-57-3

155 Bielinski, Andreas: *Numerical Simulation of CO_2 sequestration in geological formations*, 2007, ISBN 3-933761-58-1

156 Mödinger, Jens: *Entwicklung eines Bewertungs- und Entscheidungsunterstützungssystems für eine nachhaltige regionale Grundwasserbewirtschaftung*, 2006, ISBN 3-933761-60-3

157 Manthey, Sabine: *Two-phase flow processes with dynamic effects in porous media - parameter estimation and simulation,* 2007, ISBN 3-933761-61-1

158 Pozos Estrada, Oscar: *Investigation on the Effects of Entrained Air in Pipelines,* 2007, ISBN 3-933761-62-X

159 Ochs, Steffen Oliver: *Steam injection into saturated porous media – process analysis including experimental and numerical investigations*, 2007, ISBN 3-933761-63-8

160 Marx, Andreas: *Einsatz gekoppelter Modelle und Wetterradar zur Abschätzung von Niederschlagsintensitäten und zur Abflussvorhersage, 2007,* ISBN 3-933761-64-6

161 Hartmann, Gabriele Maria: *Investigation of Evapotranspiration Concepts in Hydrological Modelling for Climate Change Impact Assessment*, 2007, ISBN 3-933761-65-4

162 Kebede Gurmessa, Tesfaye: *Numerical Investigation on Flow and Transport Characteristics to Improve Long-Term Simulation of Reservoir Sedimentation*, 2007, ISBN 3-933761-66-2

163 Trifković, Aleksandar: *Multi-objective and Risk-based Modelling Methodology for Planning, Design and Operation of Water Supply Systems*, 2007, ISBN 3-933761-67-0

164 Götzinger, Jens: *Distributed Conceptual Hydrological Modelling - Simulation of Climate, Land Use Change Impact and Uncertainty Analysis*, 2007, ISBN 3-933761-68-9

165 Hrsg.: Braun, Jürgen; Koschitzky, Hans-Peter; Stuhrmann, Matthias: *VEGAS – Kolloquium 2007,* Tagungsband zur Veranstaltung am 26. September 2007 an der Universität Stuttgart, Campus Stuttgart-Vaihingen, 2007, ISBN 3-933761-69-7

166 Freeman, Beau: *Modernization Criteria Assessment for Water Resources Planning; Klamath Irrigation Project, U.S.*, 2008, ISBN 3-933761-70-0

167 Dreher, Thomas: *Selektive Sedimentation von Feinstschwebstoffen in Wechselwirkung mit wandnahen turbulenten Strömungsbedingungen*, 2008, ISBN 3-933761-71-9

168 Yang, Wei: *Discrete-Continuous Downscaling Model for Generating Daily Precipitation Time Series*, 2008, ISBN 3-933761-72-7

169 Kopecki, Ianina: *Calculational Approach to FST-Hemispheres for Multiparametrical Benthos Habitat Modelling,* 2008*,* ISBN 3-933761-73-5

170 Brommundt, Jürgen: *Stochastische Generierung räumlich zusammenhängender Niederschlagszeitreihen*, 2008, ISBN 3-933761-74-3

171 Papafotiou, *Alexandros: Numerical Investigations of the Role of Hysteresis in Heterogeneous Two-Phase Flow Systems*, 2008, ISBN 3-933761-75-1

172 He, Yi: *Application of a Non-Parametric Classification Scheme to Catchment Hydrology*, 2008, ISBN 978-3-933761-76-7

173 Wagner, Sven: *Water Balance in a Poorly Gauged Basin in West Africa Using Atmospheric Modelling and Remote Sensing Information*, 2008, ISBN 978-3-933761-77-4

174 Hrsg.: Braun, Jürgen; Koschitzky, Hans-Peter; Stuhrmann, Matthias; Schrenk, Volker: *VEGAS-Kolloquium 2008 Ressource Fläche III*, Tagungsband zur Veranstaltung am 01. Oktober 2008 an der Universität Stuttgart, Campus Stuttgart-Vaihingen, 2008, ISBN 978-3-933761-78-1

175 Patil, Sachin: *Regionalization of an Event Based Nash Cascade Model for Flood Predictions in Ungauged Basins*, 2008, ISBN 978-3-933761-79-8

176 Assteerawatt, Anongnart: *Flow and Transport Modelling of Fractured Aquifers based on a Geostatistical Approach,* 2008, ISBN 978-3-933761-80-4

177 Karnahl, Joachim Alexander: *2D numerische Modellierung von multifraktionalem Schwebstoff- und Schadstofftransport in Flüssen*, 2008, ISBN 978-3-933761-81-1

178 Hiester, Uwe: *Technologieentwicklung zur In-situ-Sanierung der ungesättigten Bodenzone mit festen Wärmequellen,* 2009, ISBN 978-3-933761-82-8

179 Laux, Patrick: *Statistical Modeling of Precipitation for Agricultural Planning in the Volta Basin of West Africa,* 2009, ISBN 978-3-933761-83-5

180 Ehsan, Saqib: *Evaluation of Life Safety Risks Related to Severe Flooding,* 2009, ISBN 978-3-933761-84-2

181 Prohaska, Sandra: *Development and Application of a 1D Multi-Strip Fine Sediment Transport Model for Regulated Rivers,* 2009, ISBN 978-3-933761-85-9

182 Kopp, Andreas: *Evaluation of CO_2 Injection Processes in Geological Formations for Site Screening,* 2009, ISBN 978-3-933761-86-6

183 Ebigbo, Anozie: *Modelling of biofilm growth and its influence on CO_2 and water (two-phase) flow in porous media,* 2009, ISBN 978-3-933761-87-3

184 Freiboth, Sandra: *A phenomenological model for the numerical simulation of multiphase multicomponent processes considering structural alterations of porous media*, 2009, ISBN 978-3-933761-88-0

185 Zöllner, Frank: *Implementierung und Anwendung netzfreier Methoden im Konstruktiven Wasserbau und in der Hydromechanik*, 2009, ISBN 978-3-933761-89-7

186 Vasin, Milos: *Influence of the soil structure and property contrast on flow and transport in the unsaturated zone*, 2010, ISBN 978-3-933761-90-3

187 Li, Jing: *Application of Copulas as a New Geostatistical Tool*, 2010, ISBN 978-3-933761-91-0

188 AghaKouchak, Amir: *Simulation of Remotely Sensed Rainfall Fields Using Copulas*, 2010, ISBN 978-3-933761-92-7

189 Thapa, Pawan Kumar: *Physically-based spatially distributed rainfall runoff modelling for soil erosion estimation*, 2010, ISBN 978-3-933761-93-4

190 Wurms, Sven: *Numerische Modellierung der Sedimentationsprozesse in Retentionsanlagen zur Steuerung von Stoffströmen bei extremen Hochwasserabflussereignissen*, 2011, ISBN 978-3-933761-94-1

191 Merkel, Uwe: *Unsicherheitsanalyse hydraulischer Einwirkungen auf Hochwasserschutzdeiche und Steigerung der Leistungsfähigkeit durch adaptive Strömungsmodellierung*, 2011, ISBN 978-3-933761-95-8

192 Fritz, Jochen: *A Decoupled Model for Compositional Non-Isothermal Multiphase Flow in Porous Media and Multiphysics Approaches for Two-Phase Flow*, 2010, ISBN 978-3-933761-96-5

193 Weber, Karolin (Hrsg.): *12. Treffen junger WissenschaftlerInnen an Wasserbauinstituten*, 2010, ISBN 978-3-933761-97-2

194 Bliefernicht, Jan-Geert: *Probability Forecasts of Daily Areal Precipitation for Small River Basins,* 2011, ISBN 978-3-933761-98-9

195 Hrsg.: Koschitzky, Hans-Peter; Braun, Jürgen: *VEGAS-Kolloquium 2010 In-situ-Sanierung - Stand und Entwicklung Nano und ISCO -,* Tagungsband zur Veranstaltung am 07. Oktober 2010 an der Universität Stuttgart, Campus Stuttgart-Vaihingen, 2010, ISBN 978-3-933761-99-6

196 Gafurov, Abror: *Water Balance Modeling Using Remote Sensing Information - Focus on Central Asia,* 2010, ISBN 978-3-942036-00-9

197 Mackenberg, Sylvia: *Die Quellstärke in der Sickerwasserprognose: Möglichkeiten und Grenzen von Labor- und Freilanduntersuchungen,* 2010, ISBN 978-3-942036-01-6

198 Singh, Shailesh Kumar: *Robust Parameter Estimation in Gauged and Ungauged Basins,* 2010, ISBN 978-3-942036-02-3

199 Doğan, Mehmet Onur: *Coupling of porous media flow with pipe flow,* 2011, ISBN 978-3-942036-03-0

200 Liu, Min: *Study of Topographic Effects on Hydrological Patterns and the Implication on Hydrological Modeling and Data Interpolation,* 2011, ISBN 978-3-942036-04-7

201 Geleta, Habtamu Itefa: *Watershed Sediment Yield Modeling for Data Scarce Areas,* 2011, ISBN 978-3-942036-05-4

202 Franke, Jörg: *Einfluss der Überwachung auf die Versagenswahrscheinlichkeit von Staustufen,* 2011, ISBN 978-3-942036-06-1

203 Bakimchandra, Oinam: *Integrated Fuzzy-GIS approach for assessing regional soil erosion risks,* 2011, ISBN 978-3-942036-07-8

204 Alam, Muhammad Mahboob: *Statistical Downscaling of Extremes of Precipitation in Mesoscale Catchments from Different RCMs and Their Effects on Local Hydrology,* 2011, ISBN 978-3-942036-08-5

205 Hrsg.: Koschitzky, Hans-Peter; Braun, Jürgen: *VEGAS-Kolloquium 2011 Flache Geothermie - Perspektiven und Risiken,* Tagungsband zur Veranstaltung am 06. Oktober 2011 an der Universität Stuttgart, Campus Stuttgart-Vaihingen, 2011, ISBN 978-3-933761-09-2

206 Haslauer, Claus: *Analysis of Real-World Spatial Dependence of Subsurface Hydraulic Properties Using Copulas with a Focus on Solute Transport Behaviour,* 2011, ISBN 978-3-942036-10-8

207 Dung, Nguyen Viet: *Multi-objective automatic calibration of hydrodynamic models – development of the concept and an application in the Mekong Delta,* 2011, ISBN 978-3-942036-11-5

208 Hung, Nguyen Nghia: *Sediment dynamics in the floodplain of the Mekong Delta, Vietnam,* 2011, ISBN 978-3-942036-12-2

209 Kuhlmann, Anna: *Influence of soil structure and root water uptake on flow in the unsaturated zone,* 2012, ISBN 978-3-942036-13-9

210 Tuthan, Jeff: *Including the Second Law Inequality in Aquatic Ecodynamics: A Modeling Approach for Alpine Rivers Impacted by Hydropeaking,* 2012, ISBN 978-3-942036-14-6

211 Tolossa, Habtamu: *Sediment Transport Computation Using a Data-Driven Adaptive Neuro-Fuzzy Modelling Approach,* 2012, ISBN 978-3-942036-15-3

212 Tatomir, Alexandru-Bodgan: *From Discrete to Continuum Concepts of Flow in Fractured Porous Media,* 2012, ISBN 978-3-942036-16-0

213 Erbertseder, Karin: *A Multi-Scale Model for Describing Cancer-Therapeutic Transport in the Human Lung,* 2012, ISBN 978-3-942036-17-7

214 Noack, Markus: *Modelling Approach for Interstitial Sediment Dynamics and Reproduction of Gravel Spawning Fish,* 2012, ISBN 978-3-942036-18-4

Die Mitteilungshefte ab der Nr. 134 (Jg. 2005) stehen als pdf-Datei über die Homepage des Instituts: www.iws.uni-stuttgart.de zur Verfügung.