
Part 1:

Palaeoflood Records – Sedimentary Archives of Past Flood Events.

2. A BRIGHT FUTURE FOR OLD FLOWS: ORIGINS, STATUS AND FUTURE OF PALEOFLOOD HYDROLOGY

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ABSTRACT

From its origins as a geological study of flood erosion and sediments paleoflood hydrology has matured to become an indispensable means of understanding the hydrology of very large, rare floods. More than 3 decades of research in paleoflood hydrology has produced spectacular advances in capabilities for (1) accurately determining paleoflood ages, (2) quantifying the magnitudes and dynamics of paleoflood processes, and (3) incorporating paleoflood data into various modeling procedures for risk assessments. Nevertheless, there are continuing controversies over the relationship of paleoflood hydrology to flood-frequency analysis and predictive modelling. These controversies may only be resolved when hydrologists resolve conflicts over the fundamental nature of their science. Regardless of the controversies, paleoflood data provide evidence of real-work cataclysms that people can understand sufficiently to alter their perceptions of hazards, thereby stimulating appropriate action toward mitigation.

1 INTRODUCTION

Paleoflood hydrologists study past or ancient floods that occurred prior to direct measurement by modern hydrological procedures. It is important to distinguish paleofloods from historical floods; the latter are interpreted from human records other than measurements with the hydrological instrumentation employed at gaging stations. Paleoflood hydrology does not rely on any direct means of human recording, either by modern instrumentation at gaging sites or by historical documentation. Instead, it is the lasting effects of past floods on the landscape, sediments, or vegetation that are appropriately documented by experienced paleoflood hydrologists at some time following the causative action of the responsible flooding.

Conventional hydrological streamflow measurements are possible because of the effects of water stages on mechanical recording devices. These effects are subsequently transformed by hydraulic theory to values of flow velocity and discharge at controlled study sites (gaging stations). For historical flood data, human observation is required, but the modern hydrological procedures employed at gaging stations do not apply. Paleoflood data derive from the effects of ancient floods on natural recording indicators, which may include flood sediments, damage to vegetation (botanical paleoflood data), and erosion of channel-margin materials. Flood stages humanly observed in historical contexts, or stages recorded naturally at paleoflood sites, can be transformed by modern hydraulic theory to velocities and discharges in analogous fashion to the data from gage sites. Note that paleofloods can be of any age; they are distinguished only by the lack of human observation or conventional

stream gaging. Moreover, there is no inherent limitation on the accuracy of such data by its being old. Accuracy is a matter to be determined from local circumstances, including the preservation of the paleostage indicator, the stability of the channel that was flooded, and the local history of change in the landscape.

2 ROCKY BEGINNINGS

The origins of paleoflood hydrology can be traced through more than two centuries of geological flood investigations (*Costa, 1987; Patton, 1987*). In recent decades geological paleoflood studies developed along several paths, which can be divided into the following categories: (1) regime-based estimates, (2) paleocompetence studies, and (3) paleostage estimates. Failure to distinguish among the characteristics of data produced by these and other varieties of paleohydrological reconstruction has led to misleading generalizations that some hydrologists have erroneously applied to all paleoflood information (e.g. *Hosking and Wallace, 1986; Yevjevich and Harmancioglu, 1987*).

Most of the modern hydrological applications of paleoflood hydrology involve the estimation of paleostages by documenting flood-induced deposition and/or erosion up to the water level reached by paleofloods. Indeed, the term 'paleoflood hydrology' was first coined for this type of study (*Kochel and Baker, 1982*). The most accurate and best-preserved records of paleostage flow data have been found to occur in stable-boundary fluvial reaches characterized by slack-water deposits and paleostage indicators (SWE-PSI) (*Baker, 1987, 2000*). Slack-water deposits consist of sedimentary particles with high settling velocities, such that they accumulate relatively rapidly from suspension during major floods. Because these sediments accumulate in areas of flow separation and slack water, such as tributary mouths, they are preserved from the erosive action of later floods (*Baker and Kochel, 1988*). Paleostage indicators are other paleo-high-water marks, which include silt that is emplaced on bedrock channel walls, scour of regolith materials marginal to the channels, the tops of cobble-boulder bars, and tree scars.

Although large floods may be very erosive within their effective flow boundaries, thereby removing the depositional evidence of earlier floods, they only add more deposits to slack-water sites lying outside of the effective flow boundaries. Thus, a typical slack-water site will preserve a sedimentary sequence of deposits representing the largest floods that occurred along the adjacent river reach. Much of SWD-PSI analysis consists of interpreting the sequence and timing of flows from these preserved sedimentary records (*Baker et al., 1979; Kochel and Baker, 1982; Baker et al., 1987*).

3 CONTINUING CONTROVERSIES

Technological advances in geochronology (1960s to present) and in hydraulic flow modelling (1970s to present) transformed the geological interpretation of ancient floods (*Costa, 1987; Patton, 1987*) into a geophysical science of quantifying the exact magnitudes and ages of paleofloods (*Baker, 2003; Baker et al., 2002*). Many countries now have research and/or practical application programs in paleoflood hydrology, with activity especially high in the United States, Spain, France, Israel, South Africa, India, Australia, Japan, and China. Nevertheless, there are also many controversies concerning the use and interpretation of paleoflood data.

3.1 Flood-frequency analysis

Paleoflood hydrology, in contrast to some portrayals (e.g. *Yevjevich and Harmancioglu*, 1987), is not one of several analytical procedures that can be directly compared to frequency curves, rainfall-runoff modelling, regionalization, Bayesian analysis, and probable maximum flood estimation. Instead, paleoflood hydrology is resource of data on very large floods that have occurred in the past. Its value derives from extending any analytical procedure by the addition of information about the real world. Particularly misleading are claims that paleoflood hydrologic “methods of flood estimation” are inherently more uncertain than are “other methods.” This uncertainty has been attributed (1) to errors in the supposed proxy relationships between data and floods (*Yevjevich and Harmancioglu*, 1987), and (2) to very large errors that are presumed to characterize individual flood value estimates (*Hosking and Wallace*, 1986; *National Research Council*, 1999). Such statements are made as generalities, as though they were the common wisdom of all hydrologists, and with little or no attention to the great natural variation in paleoflood data sources, nor to the immense scientific literature that describes the variations in those sources as faithful and accurate indicators of past flows. Paleoflood data are indexical signs of, not proxies for, real floods (*Baker*, 1998a). For appropriate field settings and interpretations, the relatively high accuracy of paleoflood data on extremely large, rare floods has been demonstrated in many studies (e.g. *Denlinger et al.*, 2002; *Jarrett and Tomlinson*, 2000; *Webb et al.*, 2002). Moreover, the degree of uncertainty can be quantified, as in other flood data, and incorporated with great benefit in various analyses of flood frequency (*Stedinger and Cohn*, 1986; *Blainey et al.*, 2002; *O’Connell et al.*, 2002).

3.2 Nonstationarity

One of the basic presumptions underlying flood-frequency analysis is that instantaneous probabilities are equated to historical frequencies of occurrence (*Klemes*, 1989). Thus, the ‘hundred-year flood’ can occur at any time with the same probability, specifically 1% in any given year. Studies of long paleoflood records (e.g. *Knox*, 1993; *Ely et al.*, 1993) show that this presumption is wrong over long time scales. Large, floods preferentially cluster in certain time periods, probably influenced by long-term trends in atmospheric circulation or oceanic sea-surface temperatures (*Hirschboeck*, 1987). The clustering of large, rare floods in time is a scientific discovery, while flood-frequency analysis is an analytical exercise that may or may not be informed by science (*Klemes*, 1986, 1987).

Mathematical treatments of flood processes commonly presume that the underlying probability distribution for the random variable of flood recurrence remains constant in time. There are two possible reactions to this nonstationarity presumption that is presumably required for rigorous flood-frequency analysis. The first reaction is exemplified by the *National Research Council* (1999) study of flood-frequency analyses of the American River in California. That study applied the term ‘bias’ in reference to long periods of flood record that are likely to include time periods during which flood probabilities are different from that applicable to the immediate planning period. The study chose to ignore paleoflood data in its flood-frequency analysis because of unease about climatic variability over the time periods of interest. It was concluded that, unless the flood magnitudes have been independently and identically distributed in time during the period represented by the paleoflood information, they cannot be incorporated with any benefit into the flood frequency analysis. The only way to overcome such ‘bias’ in the paleoflood data would be to have a “correct mathematical model” of the variations of floods in time

that would estimate flood parameters to approximately weight data from past floods. It is important to note that this conclusion is a point of view about science, not science *per se*. In expressing a contrasting point of view, *Klemes* (1997) notes that hydrological modelers have too often avoided or deliberately ignored hydrological knowledge and information. He states (*Klemes*, 1997, p. 34), "...they flaunted their hydrologic ignorance as 'absence of bias' and believed (some still do) that the mathematical rigor of models and the closeness of their fit to empirical data are the supreme guarantors of scientific objectivity and the key to true and reliable hydrologic understanding." Given this difference of opinion over scientific viewpoints in hydrology, it would seem pragmatic not to dismiss and ignore paleoflood data, but instead at least to see what these data have to tell the investigator about extreme flood phenomena.

The second response to the nonstationarity issue involves a goal of understanding the past, instead of justifying and codifying ignorance of it. In this approach the problem is one of a correct understanding of real causes (those operative in nature - what Sir Isaac Newton termed 'vera causae'), as opposed to the problem of a "correct mathematical model". In addition to the philosophical advantage of embodying well-established scientific paradigms (*Klemes*, 1986, 1987, 1989), this second response also has advantages in regard to policy and public perception (see section 4.2). One implementation of this approach is to actually identify the time periods of clustering for the extreme flood phenomena using the characteristics of paleoflood data (*Ely*, 1997). Time periods of the past that have flood distributions similar to those of current data can then be selected as extensions to the current datasets. Other time periods, with very different flood distributions, could then be used to set limits on ranges of possibilities for future climate shifts that might shift the behavior of extreme floods. Ultimately, extreme floods will be determined by the extreme storm behavior. Understanding of the causes of various kinds of floods will then avoid the ignorant mixing of populations of different kinds of flood phenomena. One would then understand floods in relation to their hydroclimatology (*Hirschboeck*, 1988), instead of in relation to untested assumptions that permit the generation of elegant (but unreal) hydrological models (*Klemes*, 1986, 1987, 1997).

4 FUTURE ISSUES

4.1 Prediction in ungaged basins

An excellent example of continuing ignorance by the mainstream hydrological community in regard to paleohydrology in general and paleoflood hydrology in particular is provided by the new International Association of Hydrological Sciences initiative 'Prediction in Ungaged Basins' (*International Association of Hydrological Sciences*, 2003). The goal of this initiative is to predict basin hydrology, despite the limited information available at most of the world's basins, and to reduce the uncertainty associated with such prediction. "Limited information" is presumed to be limited to conventional measurements at rain and stream gages. Strategies to overcome these limitations include remote sensing, statistical procedures of extrapolation from gaged basins, and, of course, model simulation, integration of meteorological and hydrological models, etc. There is absolutely no mention in the proposed program of paleohydrology as a source of information on ungaged basins. Clearly there is a need to educate hydrologists on the breadth and scope of their discipline as one means to advance their science.

4.2 Public perception

Science can either act as an authoritative basis of information, or it can work with public perception to stimulate wise responses to potential hazards, such as floods (Baker, 1998b). As a practical matter, in the public debate over responses to hazards, the documented occurrence of an ancient (but real) cataclysmic flood is likely to have more impact than is an authoritative (but highly abstract) discussion of various hypothetical probability distributions. Thus, the confirmation of flood models with paleoflood data is not merely proper science; it also serves to increase public confidence in any proposed solution that ultimately will lead to great economic or social expense for hazard mitigation. Common sense holds that what has really happened can happen again. While the probabilities of real phenomena may not be as easy to specify as those of idealized conceptualisations of those phenomena, it is the former that have the immensely greater impact on human perception. Regardless of the scientific points of view, the practical need to achieve wise action in flood mitigation requires greater attention to paleoflood hydrology than has been previously accorded.

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3. PALAEOFLOOD HYDROLOGY IN EUROPE

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ABSTRACT

Floods are the most common type of natural disaster in Europe and, in terms of economic damage, costs are increasing spectacularly with time. Besides the use of conventional hydrologic data, the pre-instrumental flood record can be completed from palaeoflood hydrology or from documentary flood information, or through the combined use of both these tools. Recent developments in palaeoflood hydrology in Europe provide (1) major improvements in flood risk assessment, and (2) a better understanding of long-term flood-climate relationships. Palaeoflood hydrology has been successfully applied in large and medium rivers as well as in small ungauged mountain drainage basins. In Europe, palaeoflood analysis can be performed within appropriate geomorphological settings of a large number of streams cutting through narrow reaches. In the European context, palaeoflood hydrology may gain from new synergies shown by its combined use with documentary records.

1 INTRODUCTION

The conventional hydrological record is usually limited to only a few dozens of years and the largest floods are therefore under represented in the data. To reduce risk associated with floods there is a critical need to increase the length of the record of extreme flood events. Information on hydrologic variability and extreme floods can be completed using either or both palaeoflood hydrology and documentary information (based on documents and chronicles). Documentary records provide a catalogue of the largest flood events which occurred during periods of settlement, and palaeoflood investigations using geological indicators can document the magnitudes of the largest floods over some period of time (from decades to millennia). Flood-deposited sediments are composed of sand, gravel and boulders although the most complete stratigraphic record is associated to fine grain size deposits. These fine-grain flood deposits are deposited either on aggradation alluvial sequences on floodplains (e.g. Starkel, 2002) or at scattered locations related to slack and back water flooded areas along bedrock canyons (e.g. Benito *et al.*, 2003). Applied palaeoflood studies follow to estimate discharges associated to individual flood units. Accurate palaeoflood discharge estimations require stable or well-known channel geometry through time, a situation usually found in bedrock channels or where alluvial channels can be shown to have been stable for long time spans. Palaeoflood hydrology have been extensively used in the USA, India, South Africa, Israel and Australia, and in recent studies in Europe. In the European context, palaeoflood hydrology shows a great potential for investigation of exceptional events in combination with documentary flood data. The European Commission funded SPHERE (Systematic, Palaeoflood and Historical data for

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the improvEment of flood Risk Estimation) project (2000-2003) represents the European effort in opening new perspectives in the joint use of palaeoflood and documentary flood data as widely integrated long-term records in conventional hydrology and engineering flood studies.

2 FLOOD RECORDS FROM FLOODPLAIN DEPOSITS

More than half of Europe consists of lowlands; these include the East European Plain in the east (more than 3,200 km wide from north to south); the North European Plain, which covers Poland, northern Germany, southern Scandinavia, Belgium, The Netherlands, and northern and western France; the Romanian, Bulgarian, and Hungarian plains; and southern Finland. Many of the major European rivers (Volga, Danube, Dnieper, Don, Rhine, Vistula, Elbe, Rhône, and Oder) cross these lowlands, developing extensive alluvial floodplains. Therefore, in Europe, most common sedimentary flood records correspond to overbank flood deposits (e.g. Vistula River, Starkel *et al.*, 1996). One of the most complete sequence of overbank flood deposits has been documented in the Vistula valley providing phases of higher flood frequency at about 8500-7700, 6500-6000, 5200-4400, 3000-2600, 2200-1800, 1000 and 400-100 yr BP (Starkel, 2002), which can be related to climatic or environmental changes. These alluvial channels are unstable with fluctuations that can reach tens of metres within periods of several thousand years. This channel mobility prevents its use in discharge estimation. In some cases, channel stability during the period of the palaeohydrologic record can be evaluated using several techniques (Webb and Jarrett, 2002) and eventually used in discharge estimates for palaeoflood analysis. In Europe, channel cross-section data extending back several hundred years can be obtained from documentary sources and used in combination with geological evidences of flooded areas for hydraulic calculations.

3 PALAEOFLOOD RECORDS FROM SLACKWATER FLOOD DEPOSITS

River channels cutting through hard bedrock or other resistant boundary materials (e.g. cemented terraces) provide the most suitable settings for reconstructing the palaeoflood record (Baker *et al.*, 1983) as they are the most conducive to the accumulation and preservation of flood deposits and palaeostage indicators (PSI's). PSI's include slackwater deposits (SWD; within sedimentary environments such as eddy bars, flood deposit benches and deposits at tributary mouths), and bedrock scour features. During flood stages, eddies, back-flooding and water stagnation occur at marginal areas of the channel, producing low velocities and/or flow stagnation (slack water) which favours deposition from suspension of clay, silt and sand. These fine-grained deposits can be preserved in stratigraphic sequences (Benito *et al.*, 2003b) providing detailed and complete records of flood events that extend back several thousand of years (Baker *et al.*, 2002). Numerical dating using radiocarbon ($C-14$) and luminescence methods (thermo- (TL) and optically stimulated- (OSL), for example) is obtained, through collection of organic (seeds, charcoal, wood debris, etc.) and sand samples, respectively. The discharge estimation of the different flood units/features can be accomplished by computing the water surface profiles for various hypothetical discharges that are routed through the river reaches. By comparing the model-generated profiles to the palaeostage indicators (slackwater flood deposits, erosional features, geomorphic bounds, etc.) or historical flood levels probable palaeodischarges can be specified.

In Europe, relatively few sites (see Figure 1) containing SWD have been described (*Benito et al.*, 1998, 2003a; *Woodward et al.*, 2001; *Sheffer et al.*, 2003; *Sheffer*, this volume; *Thorndycraft et al.*, this volume). In Spain, palaeoflood studies have been successfully applied in large basins (e.g. Tagus river, Central Spain; *Benito et al.*, 2003), in medium size basins (Llobregat river, NE-Spain; *Thorndycraft et al.*, this volume), and in small mountain drainage basins of the Pyrenees (*Rico et al.*, 2001). In the Tagus river (Central Spain), a long-term SWD palaeoflood record, with more than 80 flood events, shows clusters of floods at specific periods from 8540-8110 BC, 7500-7000 BC, ~5000 BC, AD 785-1205, AD 1450-1500, AD 1670-1950. The largest flood(s) occurred during the periods 8540-8110 BC, ~5000 BC and AD 785-1205 reaching minimum discharge estimates exceeding the largest floods from the instrumental record (*Benito et al.*, 2003a).

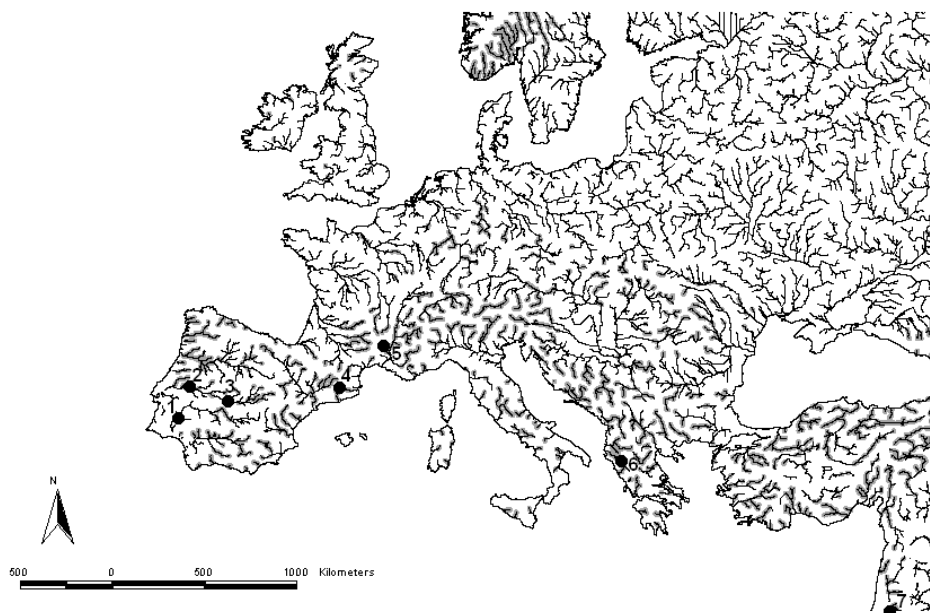


Figure 1. Map showing the a first cut of potential reaches suitable for palaeoflood studies (grey highlight reaches; see text for explanation), versus the distribution representative actual SWD-PSI palaeoflood sites in the region. Many more studies on floods from sedimentary records using overbank deposits have been done. 1. East-Central Portugal (*Ortega et al.*, this volume). 2. Western-Central Spain (*Benito et al.*, 2003). 3. Central Spain (*Benito et al.*, 2003a,b). 4. Northeastern Spain (*Thorndycraft et al.*, this volume). 5. *Sheffer et al.*, 2003 and this volume). 6. Northwestern Greece (*Woodward et al.*, 2001). 6. Negev Desert (*Greenbaum et al.*, 2000).

4 POTENTIAL FOR PALAEOFLOOD STUDIES IN EUROPE

Palaeoflood hydrology has obtained, after three decades of intensive research in different parts of the world, scientific credibility and recognition as an effective tool for numerous applications in understanding flood occurrences and the evaluation of flood hazards (*Baker et al.*, 2002). In Europe, palaeoflood hydrology is still a developing field

with a great potential for being complemented for the last thousand years with detailed documentary records.

As indicated previously, palaeoflood analysis is most suitable within stable channels which satisfy hydraulic model assumptions. Other factors controlling the accumulation of SWD are: 1) alternation of expansion and constriction reaches along the bedrock canyons, 2) low to medium channel slope - in contrast to high-energy environments which transport gravels and boulders-; 3) abundance of fine-grain sediment source available in the catchment –ready to be transported as suspension load.

Considering some of these factors, a first approximation to highlight river reaches with potential for palaeoflood studies can be obtained from GIS analysis. Information layers used in this analysis included: 1) stream network data set derived by thresholding the flow accumulation data set at 1000 km², i.e. streams with low to medium channel slope; and 2) slope terrain data describing the maximum change in the elevations between each cell (1000 m pixel size) and its eight neighbours which is expressed in integer degrees of slope between 0 and 90. Slope terrain data describes areas of relief contrast in which gorges or narrow river reaches can be developed. It was assumed that slope data ranging between 2.5 to 7.5 integer degrees were most suitable for describing these narrow reaches outside of mountain areas. Figure 1 shows the results of the GIS graphical intersection between the stream network data set, and slope terrain data (2.5 -7.5 integer degrees). This preliminary analysis shows a large number of rivers mainly located in the Mediterranean riverine countries and at particular reaches of central European rivers with narrow and/or gorge reaches suitable for palaeoflood analysis. In addition, this coarse analysis point out the extensive areas with potential for palaeoflood studies, mainly in southern Europe, and the need for developing new methodologies applicable for alluvial channels.

It is clear that potential use of palaeofloods integrated into the realm of traditional flood practice will depend upon our ability to address the standardisation of methodological procedures of reconstructing past floods and to develop tools (methodologies and software) for its efficient integration into flood frequency analysis for flood design and planning. The EU-funded SPHERE project aims to contribute to the improvement of methods directed towards the reconstruction of past flood peak discharges, and to work on the production of “best practice” guidelines to follow a broad use of non-systematic data (palaeo and documentary data). SPHERE shows excellent examples on how past flood information (palaeoflood and historical floods) contributes to understand extreme floods, occurring probably once in 100 or 150 years, but which are the most destructive and damaging to society (e.g. last summer floods in central and southern Europe). The most recent example corresponds to the Gard River in southern France where an extreme flood of historical magnitude occurred on the 8-9 of September 2002, claiming the lives of 21 people, and causing millions of Euros worth of damage to the towns and villages along the river. The magnitude of this flood is larger than any historical flood on record. Palaeoflood studies within the SPHERE Project in that area (*Sheffer et al.*, 2003) reveals the occurrence of several past extreme floods of even greater magnitude than that of the 2002 flood, and therefore larger than any observed flood that has occurred in the recent past. The palaeoflood record, in most cases exceeding 1,000 years in length, can be incorporated into flood-frequency analysis (*Ouarda et al.*, this volume). Many researchers have emphasised the potential gain of the statistical methods for estimating flood quantiles by the use of palaeoflood and documentary information. Because palaeoflood and documentary floods are large by definition, their introduction into a flood frequency analysis improves the estimates of the probabilities of rare floods. This is particularly true when 3-parameter

distributions are considered. This palaeoflood information is ideally suited for flood hazard studies both for the delineation of flood prone areas with high levels of desired and/or tolerated protection against floods and for hydrological design of structures at risk for extreme floods (e.g. dam design). Hydrologic design of high-risk structures such as design flood assessment for dam safety, or floodplain delineation for nuclear power plants, currently obtained using the probable maximum flood (PMF), can also benefit from palaeoflood hydrology. So far, the PMF is obtained from a combination of meteorological and physical assumptions producing a valuable but uncertain result. In some cases, the PMF appears to be unreasonably large in comparison to the palaeoflood record (*Levish* 2002). Incorporation of palaeoflood data into flood-frequency analysis offers a mean for evaluating whether a PMF is reasonable or not (*Baker et al.*, 2002), and to provide statistical meaning to a calculated PMF (*Francés & Botero*, this volume).

In terms of the hydrological effects of climate change, future global circulation model projections incorporate too much uncertainty to accurately specify expected patterns of precipitation change, and even less the frequency and magnitude of extreme storm and flood events. Predictions can be improved by incorporating long-term flood records (several millennia) in climatic modelling and statistical analysis. The study of temporal variability of past climate-flood links can establish short- and long-term relationships at regional levels and in areas within different climatic zones (*Benito et al.*, in press). Regional studies of long-term climate-flood links involve calibrating the relationships, detecting trends (where they exist) and revising estimates of return periods. This integration will greatly advance our understanding of flood frequency and magnitude in the context of changing climates where the assumption of stationarity (implicit in most current flood risk models) is being questioned.

European palaeoflood studies can take advantage from long documentary records (last 1000 years) which describe extreme flood occurrence (exact dates) and produced damages. The best scenario combines palaeoflood discharge estimates from bedrock canyons with documentary description and quantification of flood impacts on past societies, including economic losses, recovery strategies and flood management at different periods. The history of past floods, such as the one that occurred in 1617 in NE-Spain (*Barriendos*, 1996-97) provide a unique opportunity to understand the flood hydrology and the social impact of "catastrophic floods" with magnitudes far beyond the ones recorded at gauge stations. This, in turn, means gaining an understanding of individual extreme events not available and perhaps not predicted by the instrumental record, as well as to gain a new dimension on socio-economic impacts and perception of extreme events, which needs to be evaluated according to different historical contexts. Flood damage exerted on riverside societies during centuries is very valuable information to be used in risk education tasks directed to Civil Protection technicians, volunteer bodies and in schools.

5 CONCLUSION

In the investigation of the environmental effects and risks associated with fluvial systems in natural and anthropogenic disasters, the participation of multidisciplinary groups made up of geomorphologists, sedimentologists and hydrologists, mathematicians and environmental managers is increasingly called for. The appropriate analysis of hydrological risks is dependent upon the development of new methods in the field of palaeoflood hydrology as a complement and/or alternative to instrumental hydrology. These should allow the standardization of discharge estimation procedures and flood risk assessment

using non-systematic data for small watersheds devoid of gauging stations, and also improve the estimation of peak discharges for floods of long return periods (500 and 1000 years) aimed at increasing the safety of dams. In the present perspective, the European Commission funded project, SPHERE, provides a step-forward in this respect. This project was set up for preparing a methodological approach, fitting with European needs and type of data available, for understanding floods through the analysis of past and present flood events and for developing statistical and meteorological tools for flood risk prevention. These tools based on past flood information will no doubt serve to inform decision-makers on the real risks that floods will pose to their citizens.

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4. PALEOFLOODS IN SOUTHERN FRANCE –THE ARDÈCHE RIVER

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ABSTRACT

The integration of gauged, historical and paleoflood data of the Ardèche River allows for better understanding of flood occurrences, and long-term, knowledge-based floodplain planning for flood risk assessment. The Ardèche River is ideal for this historical-paleoflood study because its historical record dates back as early as AD 587; its systematic gauging record is over 100 years long; and the geologic and geomorphic settings are optimal for paleoflood studies. An abandoned meander 19 m above the river base flow is an obvious threshold for floods in the Ardèche River gorge. Our 1D step-backwater calculations using the HEC-RAS hydraulic model reveal that the meander threshold is 5200-5700 m³ s⁻¹. Four late Holocene and two middle Holocene floods are apparent in the meander. Dating these deposits enabled the correlation of the late Holocene paleofloods with the historical floods.

1 INTRODUCTION

Historical and paleoflood data are used to extend the flood record beyond the gauged record (e.g. Benito *et al.*, 2000). Paleoflood hydrology is based on geomorphic, sedimentologic and hydrologic analysis of floods that occurred prior to systematic measurements and mainly of late Holocene floods. This branch of geomorphology and hydrology provides the needed long-term perspective on extreme floods.

The largest flood on record in the Ardèche River, southern France, peaked on September 22nd 1890, lasted 3 days, killed dozens of people, and caused extensive damage. This specific flood is considered to be >100-year-flood (C. Gigon, *personal communication*, 1999) as computed from more recent floods but a long-term perspective on its frequency and magnitude is desirable.

In this research we recovered the record of the largest floods in the Ardèche River during the late Holocene by using paleoflood hydrology methodologies. As quantitative paleoflood records are the exception in Europe (Benito *et al.*, 2000), this effort should be seen as a first step toward compiling a database on large past floods. In the future such a database will allow regional analyses and testing climate-flood relationships.

2 THE ARDÈCHE RIVER BASIN

The Ardèche River (2350 km², 150 km in length) (Figure. 1) located in the southeast of the Massif Central (Cévennes Region, France) heads at ~1600 m above sea level (ASL) and merges with the Rhône River at 37 m ASL. The three main tributaries of the Ardèche River flow within deep and narrow northwest-southeast valleys incised in magmatic and metamorphic rocks. In its lower southeast reach the main stem of the river has a gorge

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within carbonate rocks. The Ardèche is a perennial river with an average annual peak discharge of $700 \text{ m}^3 \text{ s}^{-1}$.

Historical data of the Ardèche floods dates back to the 6th century (*Roudil, 1991*). Obviously, as we go back in time, the quality of the information is compromised as a result of the subjective nature of the data. Furthermore, population expansion through time occurred in areas previously unoccupied, increasing flood hazard/impact and enhanced the recording of the event in memory and historical documents, while the actual events were no different than those before habitation.

The long gauging record is an extensive database to work with and consists of: automated measurements since the 1950s; systematic stage since 1897; and continuous stage observations dating back to the middle 19th century (*Naulet et al., 2000*). The geological settings are ideal for such studies as shown in Figure 1.

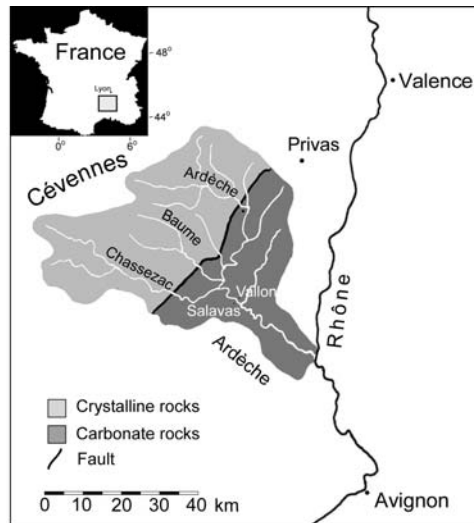


Figure 1. Location map of the Ardèche River Basin, in the Cévennes Region of the Massif Central in Southern France. It flows into the Rhône River. The upper reaches of the catchment are incised in magmatic and metamorphic bedrock, and are separated by a fault from the lower reaches, which are incised in carbonates. The contrast between the magmatic and metamorphic bedrock of the upper catchment and the carbonates of the Ardèche lower gorge makes it easier to identify flood sediments transported into the gorge. The bedrock gorge enables us to assume only minor changes in the morphology of the gorge during the late Holocene (*Baker et al., 1983*). The carbonate rocks exposed along the canyon have many karstic caves and alcoves, which add another advantage; they are traps/sites for slackwater deposit accumulation from extreme floods (*Baker, 1987*).

3 METHODS

The paleoflood study was conducted through analyses of slackwater deposits (SWD) (*Baker, 1987*) in the Ardèche River. The SWD elevations were used to estimate the stage of the peak discharge of the flood. The sequence of flood deposits is then dated by radiocarbon (e.g. *Baker et al., 1985*) and optically stimulated luminescence (OSL) (*Aitken, 1998; Forman et al., 2000*).

Using cross-sections, from detailed topographic maps and field survey, we performed step backwater calculations using HEC-RAS 3.0.1 (*USACE-HEC*, 1998). This 1D gradually varied flow model calculates the water surface profiles associated with specific discharges. The basic concepts of the applications of these calculations to paleoflood hydrology are outlined in *O'Connor & Webb* (1988). Many examples exist for the use of the HEC models for the reconstruction of paleofloods from SWD (e.g. *O'Connor*, 1993; *Enzel et al.*, 1994; *House et al.*, 2002).

4 PALEOFLOOD DEPOSIT SITES

Paleoflood fieldwork was carried out at the lower reach of the Ardèche River, downstream of the village of Vallon Pont d'Arc. Pont d'Arc, a natural arc is situated 4 km downstream of the village, and 2 km into the confined gorge. Immediately upstream to this arc is an entrance to a meander that was abandoned by the river when the new route through the arc was created (Figure 2). Since the prehistoric abandonment of the meander and deposition in the meander the river normal flow is now 19 m below the meander making it a trap only for deposits associated with flood higher than 19 m. In addition, deposition of sediment during the largest floods probably caused the rise of the thalweg of the abandoned meander in relation to the thalweg of the active bedrock channel. In many respects the meander acts almost as a spillway, discharging excess water and bypassing the arc downstream during large floods.

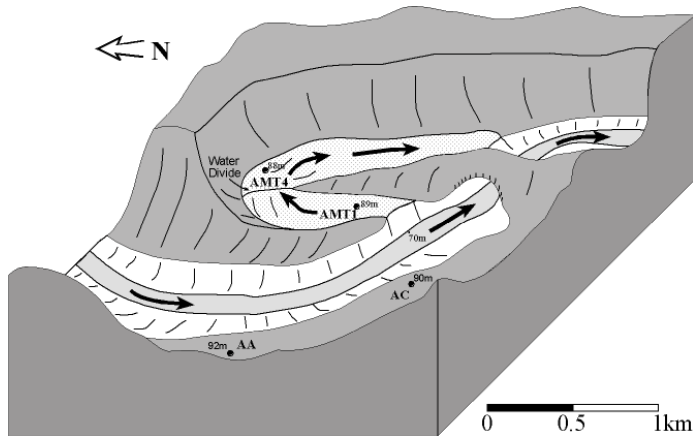


Figure 2. The arch of Pont d'Arc and the abandoned meander, where we concentrated our work. Before the prehistoric formation of the arch, the river flowed through the meander. Now the river flows through the arch and during extreme floods the water rises to the meander threshold, which acts as a spillway. The SWD sites AMT1 and AMT4 are shown here.

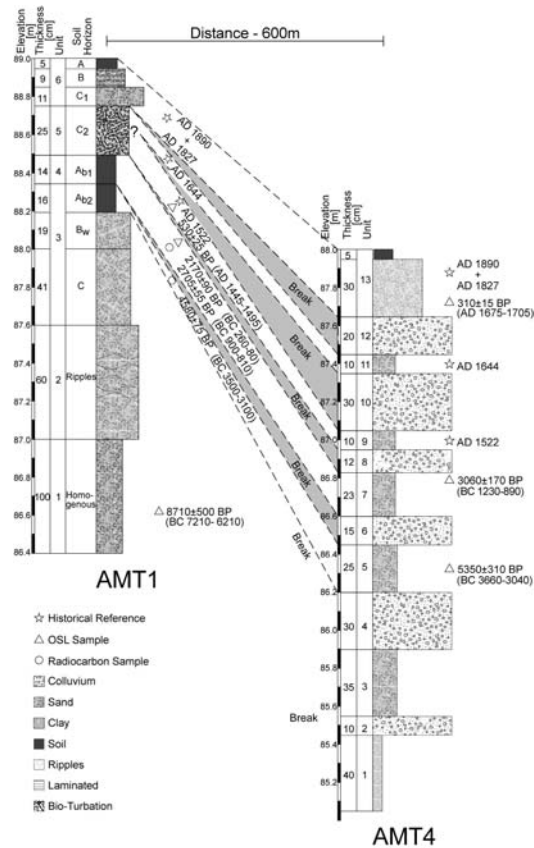


Figure 3. The stratigraphy identified in the two trenches dug 600 m apart. (a) AMT1, in the beginning of the abandoned meander is 2.6 m deep showing 6 depositional units. (b) AMT4, halfway through the meander, is 3 m deep and has 13 depositional units. The top units at sites AMT1 (unit 6) and AMT4 (unit 13) represent the last time the meander was active. According to historical information, the meander was active during both the AD 1890 and AD 1827 floods. The short break between these events, and agricultural activities carried out in the meander, may have caused a difficulty in discerning them apart. Furthermore, the base of unit 13 at AMT4 was dated to AD 1675-1705, which could represent the AD 1827 flood when dealing with OSL ages. The next two extreme historical floods are the AD 1644 and AD 1522, which are represented in AMT1 by unit 5, and at AMT4 by units 11 and 9. The base of unit 5 at AMT1 was dated to AD 1445-1495, which probably represents the AD 1522 flood. Unit 4 at AMT1 is a buried soil A-horizon. The humic acids in it were dated by radiocarbon to BC 260-80, which could be treated as a minimal age. This unit was also dated by OSL to BC 900-810. This unit correlates to unit 7 at AMT4, which was dated to BC 1230-890. The top horizon of unit 3 is an organic A-horizon, dated to BC 3500-3100. This unit correlates to unit 5 at AMT4 dated to BC 3660-3040. Site AMT1 is farther from the canyon walls (Figure 2), thus breaks between events are noticeable only by the change in characteristics sediments (grain size, color and hue). Site AMT4 is near the cliff (Figure 2) and accumulates colluvium (units 2, 4, 6, 8, 10, and 12) during long breaks in floods.

4.1 Sites AMT1 and AMT4

The stratigraphy at these sites is based on trenches dug in the meander. Six depositional units were distinguished at AMT1, and seven flood units at AMT4. The exposure of the meander surface to pedogenesis may cause some units to reflect fewer floods than actually occurred. The high rate of soil development in this area due to the wet climate may cause welding of different soils from separate relatively thin flood deposits. A good correlation (Figure 3) was established between sites AMT1 and AMT4 by comparing dated units. We could also relate our findings to the historical records. The four largest floods on record are probably the AD 1522, 1644, 1827 and 1890 floods. According to each of the sites AMT1 and AMT4, and this correlation, the meander was flooded four times during the latest Holocene, and twice during BC 3660 to BC 80 (Figure 3).

The results of the step-backwater calculations show that once water begins to flood the meander the discharge is $5200\text{--}5700\text{ m}^3\text{ s}^{-1}$. This range is a result of wide range Manning- n values used (0.3–0.6) (Figure 4). The meander threshold elevation is rising through time, due to deposition of sediment during extreme floods. As the meander aggrades, the spillway threshold rises, and the water stage upstream of it can rise without being drained through the meander. Therefore, in subsequent floods the higher entrance to the meander will cause a larger back flooding upstream, affecting the villages of Vallon Pont d'Arc and Salavas and their surrounding valleys.

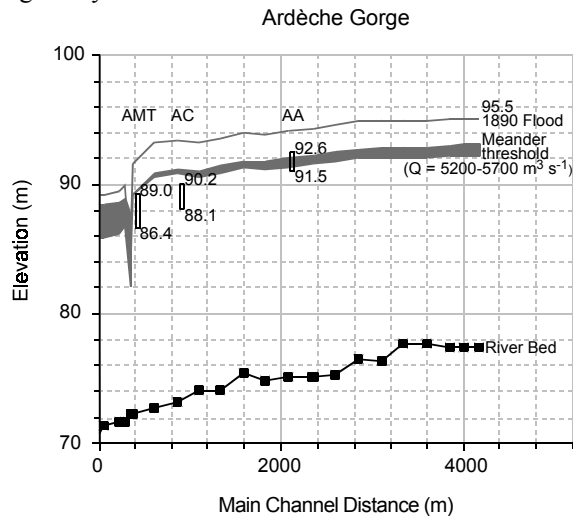


Figure 4. Water surface profiles calculated with HEC-RAS. The meander threshold for flooding is $5200\text{--}5700\text{ m}^3\text{ s}^{-1}$. The 1890 flood, which reached 95.5 m above sea level at the Vallon Bridge, $6500\text{ m}^3\text{ s}^{-1}$ or more.

In this study we identified 6 floods that were large enough to pass the meander's rising threshold during the middle to late Holocene. Four of these floods were clustered during the Little Ice Age (LIA; Grove, 1988). The events prior to this cluster occurred more than 2000 years earlier creating a large temporal gap in occurrences of extreme floods. This long interval is manifested by the well developed buried soils encountered in site AMT1, and the large gaps identified in site AMT4. Therefore it is claimed that the largest floods in the meander are very rare in the late Holocene time scale, and are less frequent than estimated

(0.2%) by Lang & Recking (2002), based on the measured and historical information alone. All the late Holocene events cluster within the relatively short LIA.

A similar clustering of LIA floods was observed also in the Gardon River, south of the Ardèche River, which is affected by the same storm systems (Sheffer et al., 2003). Thorndycraft et al., (this volume) show similar temporal pattern in the occurrences of the largest floods in the eastern Spanish Pyrenees; clustering during the LIA following a ~2000 year long gap.

5 CONCLUSIONS

A relatively good agreement between the largest historical floods and paleofloods of the Ardèche River during the late Holocene has been achieved. The natural threshold selected in this study enabled the isolation of the largest floods of the Ardèche River in sites that recorded and preserved SWD as well as no-flood (flood-break) episodes.

Paleoflood hydrology is widely used around the world, especially in arid and semi-arid regions, but was considered less effective in humid regions (e.g. Kite and Linton, 1993). This work shows that this method can and should be used in suitable humid regions.

Despite the known problems with the dating techniques used, i.e. wiggles in the radiocarbon calibration curve and bleaching of the OSL samples, the excellent agreement between these two methods documented in this study indicates the efficiency of these methods in analyzing flood deposits.

The large floods identified in this study were clustered during the Little Ice Age, as in other basins in southern France and northern Spain. The clustering of these floods follows a long period (>2000 years) of no evidence of large floods. Therefore, we postulate that we observe a real regional change in the hydroclimatic patterns during late Holocene, which is related to the interaction of western Mediterranean moisture and North Atlantic storms that currently cause extreme floods on these areas during the fall. Furthermore, based on our findings stationarity cannot be assumed.

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5. PALAEOHYDROLOGY OF THE LOWER GUADIANA RIVER BASIN

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ABSTRACT

Palaeohydrology using slackwater flood deposits (SWD) is a useful technique in order to understand river flood magnitude and frequency. Systematic gauge station records for the Guadiana River, and for most of the Iberian Peninsula, begin in 1912, however, only a few stations preserve a continuous, reliable record on which to base detailed hydrological reconstructions. In the towns of Badajoz and Merida, as in various other riverine towns along the Guadian River, both in Spain and Portugal, there are historical marks indicating that the highest flood-level on record is that of 1876. With an estimated discharge of 10,000m³/s at Badajoz, this flood is considered a major point of reference for estimations of return periods. SWD have been studied on the lower Guadiana River in order to understand the significance of historical floods in the context of palaeoflood records. In the lower Guadiana River at least seven floods, starting from 3260BP, have been identified as slackwater deposits. Several of them were larger than the greatest in the historical record, that of 1876AD.

1 INTRODUCTION

Palaeofloods were studied using palaeoflood hydrological techniques in order to estimate peak discharges in the lower basin of the Guadiana River. These palaeofloods occurred in the absence of gauging data and historical records (HR) generally. There is a long HR of flooding in the Guadiana basin. Unfortunately there are very few cases in which there are sufficient hydrological data on record for reliable reconstructions of return periods.

In some cases it was possible to establish relations between slackwater deposit-palaeostage indicators (SLW-PSI) and historical floods by dating some of the deposits using the ¹⁴C standard and AMS methods. Verifications were also made by ¹³⁷Cs. SLW-PSIs produce the most accurate estimates of palaeoflood magnitudes (Baker, 1989) and can be combined with the HEC-RAS hydraulic calculation program to establish discharge estimates.

In a previous paper, and on the basis of the various records of historical floods, the meteorological data (Ortega & Garzón, 2002) and discharge estimations, we were able to verify the relationship between historical floods and meteorological phenomena by means of analysis of the seasonal and annual distribution of precipitations and floods.

2 BASIN CHARACTERISTICS

The river Guadiana is one of the largest in the Iberian Peninsula; it is the fifth in terms of discharge and length, with a hydrological basin measuring 66,800 km² in a semi-arid environment (rainfall 400-500 mm/year). It crosses the Península from East to West, traversing various different geological units before flowing into the Atlantic Ocean.

The Guadiana canyon in the Serpa area (Portugal) was chosen for its good depositional conditions, the possibilities of hydraulic modeling, and also because there is a gauge station with records going back to 1941.

3 HISTORICAL RECORD

In order to understand and to characterise flooding and flood frequency within the Guadiana basin, a record of 128 floods since 680 BC was compiled for the whole basin from different sources (Comisión Nacional de Protección Civil, 1985, Ayala et al., 1986 Ortega & Garzón, 1997 and Font Tullot, 1998,) and analyzed within their geomorphologic and climatic framework. Floods were distributed by decades, starting from the first concrete historical records in 1500 and considering only floods affecting the main river, that means large winter floods produced by Atlantic frontal systems. Floods were classified in order of relative magnitude as deduced from the existing information. There are several large floods between 1500 and 1900 that can be related to periods of greater fluvial activity during the Little Ice Age (LIA) and an increase in floods in the second half of 1800 (Figure 1). In recent times there has been an increase in the number of floods, however, they cannot be analysed together with the historical data due to dam construction, demographic growth and human occupation in flooded areas.

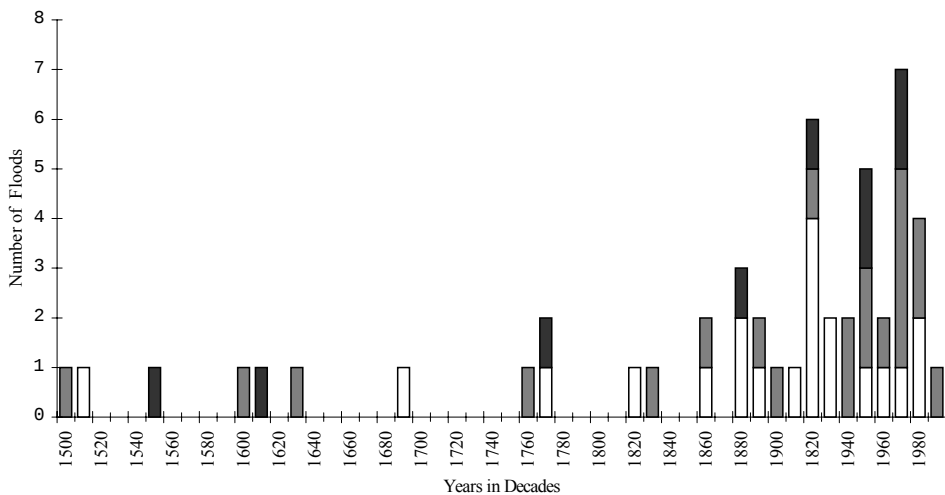


Figure 1. Decadal distribution of floods in the main river. Colour gives an interpretation of relative magnitude (Dark : large floods, grey: medium floods, white: small floods).

4 PALAEOHYDROLOGICAL RECORD

4.1 Palaeohydrological analysis

Systematic gauge station records for the river Guadiana, and for most of the Iberian Peninsula, begin in 1912. However, only a few stations preserve a continuous, reliable record on which to base detailed hydrological reconstructions. Palaeohydrological analysis, using palaeostage indicators (PSI), such as slackwater flood deposits, provides more information in order to lengthen the flood record.

4.2 SLW location and reach geomorphology

In the lower course of the Guadiana River, near the Portuguese town of Serpa, is the Pulo do Lobo canyon. This reach of the river is enclosed by metamorphic materials forming a steep-sided gorge. The valley is 400m wide. The surface area of the Guadiana in this reach is 60,800Km².

It is in this canyon that the principal slackwater (SLW) deposits have been identified, essentially at four main locations: Arroyo de las Limas cut (Site 1, samples CAL), gauge station cut (Site 2, sample CEA), Arroyo 1 cut (SITE 3, samples CA1) and Arroyo 2 cut (Site 4, samples CA2). All the deposits described are on the left bank of the river and form benches backing on to the valley walls in ponding and eddy bar zones. They are situated at the confluence of major tributaries like Arroyo de las Limas (Site 1) and other smaller creeks (Sites 3 and 4). Site 2 lies at the exit of a narrowing of the canyon, level with the Pulo do Lobo gauge station..

From a geomorphological point of view, the studied river reach displays special hydraulic characteristics. The Guadiana has eroded a deep gorge in the Palaeozoic metamorphic substratum. The gorge shows the distinguished bedrock channel morphology described by Shepard & Schumm (1974). The valley bottom consists of a wide bedrock platform, incised by a deep and narrow inner channel. This single channel conveys all the river flow at normal stage during a high frequency flood. The inner channel does not appear all along the studied reach, it starts at a knickpoint formed by a 16m high waterfall close to Site 3. During large floods the flanking bedrock benches are covered by the floodwater.

The bedrock bench remains perched like a strath-terrace for most of the time, only covered by water during medium to high floods. The shape of the channel will be determined by the minimum variance in energy between reaches (Wohl et al 1999), considering that the principles of uniform energy expenditure might be also applied on bedrock channels by a relatively homogeneous substratum.

However, what most influences hydraulic behavior is the presence of a bedrock bench which acts as a floodplain during high-water periods and is controlled by the larger floods, as is the formation of the inner channel. This is the true channel that controls the flow dynamics under which slackwater deposits are formed and situated at different heights.

4.3 Dating and interpretation

Two methods have been used to date the SLWs. One is ¹³⁷Cs (Ely et al, 1992), used to determine whether the deposit is earlier or later than 1952, the year in which the nuclear emissions of this element first began. The other and principal method is ¹⁴C. Analysis by the ¹⁴C Standard method has shown that results are not always very satisfactory in these cases. Samples were dated by BETA Labs. The results are shown in the Table 1.

4.4 Flow model and discharge estimation

The mathematical model used was Hec-Ras version 2.0, developed by the Hydrologic Engineering Center (Hec-Ras, 1997), with stationary flow and step backwater flow characteristics. The hydraulic model was built up following the SWD-PSI methodology, accepting a number of assumptions (O'Connor & Webb, 1988, Hoggan, 1989, Baker, 1989, House & Pearthree, 1995): (1) Steady flow, gradually varied, and one dimensional, (2) Energy slope is uniform between cross sections, (3) Channel cross section boundaries are stable, and (4) PSIs approximate the stage of the floods considered. SWD represent a minimum peak flood stage, flotsam represents the highest water surface. A recent flood, of 1987, served to verify the flow characteristics and the water surface profile at the Pulo do Lobo gauge station (27L/01). This is a reliable control for the model and was used to verify the base hypothesis in order to achieve the best contour conditions. The discharge estimates are presented in Table 1, along with dating information for each flood deposit.

SLW unit	Topographic level	C-14 Standard	C-14 AMS	Cs-137 (pCi/g)	Historical flood Interpretation	Discharge (m ³ /s)
AL0	57.2		300+/-60 BP		1603	15,500
AL1	53.1m	"Modern"		0.13+/-0.01	-	
AL2	55.7m			0.05+/-0.01	1955<	
AL3	54m		3260+/-40 BP	0	3260BP (*)	11,900
AL41	52m		90+/-40 BP		-	
AL44	53m	130+/-60 BP			1758	10,900
A172	50.3m		290+/-30		1545	10,200
A173	50.9m	60+/-50 BP			1876	10,600
EA6	50.9m	60+/-60 BP		0.05+/-0.01	1876	10,600
A291	51.8m		90+/-40 BP		-	
A292	52.1m		1180+/-40 BP		1180BP (*)	10,000
A293	52.4m		710+/-40 BP		710BP(*)	10,400
A294	53m		130+/-50 BP	0	1758	10,900

Table 1. Some slackwater units and its corresponding datation, interpreted historical flood and estimated discharge. (*) No historical record on this calendar ages.

4.5 Interpretation and magnitude

In the towns of Badajoz and Merida, as in various other riparian towns of Spain and Portugal (Mértola, Sanlúcar de Guadiana, Alcoutim), there are historical marks defining the height reached by the waters. All these marks indicate that the highest flood-level on record is that of 1876. With an estimated discharge of 10,000m³/s at Badajoz, this flood is

considered a major point of reference for estimations of return periods. This flood was considered till now, as the 500 year return period one, but after the use of palaeohydrological methods we propose a change to a 100 year flood for it. The new frequency coincides better with the Snirh, (1999) estimations in the Table 2 below.

Gauge station	Basin area (Km ²)	Mean annual peak discharge (m ³ /s)	Return Period (year)				
			10	50	100	500	1000
Pulo do Lobo Before 1965	60883	3206	6391	9535	10865	13936	15257
Pulo do Lobo After 1965		2249	4905	7527	8636	11197	12298

Table 2. Return period estimated for the Pulo do Lobo reach with two estimations after and before 1965 age of new regulated situation with three large dams (Snirh, 1999).

5 CONCLUSION AND DISCUSSION

Historically, the largest flood for which height levels remain was that of 1876AD, which devastated several towns and villages along the river basin. At Badajoz, some 100 km upstream from the studied zone, the estimated discharge was 10,000m³/s. More recent estimations suggest that the flood may have reached 10,600m³/s, which places it only in fourth to sixth place in the range of our studied floods.

According to our own findings, there have been at least two higher floods in relatively recent times: those of 1758AD and 1603AD. The latter is the highest in the entire sedimentary register that we have compiled throughout the studied reach, and these data are not inconsistent with the conclusions reached previously in the historical record. In addition, there is a very old record, of 3260BP, with a discharge of almost 12,000m³/s, which has been preserved by the deposition of more recent levels.

For the Tagus and Guadiana basins, Benito et al (1998) identify an increase in the number and magnitude of floods during three periods: 1150-1290AD, 1400-1500AD and 1800-1910AD. There are few data available before 1500 for the Guadiana River. Ortega and Garzón (1997) identify increased flooding between 1500AD and the beginning of 1600AD in the LIA period. Other important periods are around 1700AD, and a main period running from about 1850AD to the beginning of the last century. The data analyzed need to be processed further and compared with interpretations at other points in the basin where work is currently proceeding.

Acknowledgments. This research has been supported by CYCIT Project N° HID96-1318/96, and DGEISIC Project N° PB98-0846.

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6. RADIOCARBON AND CAESIUM-137 DATING OF SLACKWATER FLOOD DEPOSITS OF THE LLOBREGAT RIVER (NE SPAIN)

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ABSTRACT

The palaeoflood hydrology of the Llobregat River in Catalonia, NE Spain, was investigated using slackwater flood deposits preserved in rock alcoves along two gorge reaches of the Llobregat: 1) Pont de Vilomara and 2) Monistrol de Montserrat. Initial chronological data, derived from AMS radiocarbon dating of charcoal found within individual flood units, yielded a range of ages from ca. 2700 yrs BP to modern. The potential use of ¹³⁷Cs was evaluated to improve the chronology of the modern flood deposits. The technique was successfully applied to a sedimentary profile of the Monistrol reach, enabling improved correlation between the sedimentary and instrumental flood records. At Vilomara, however, in an alcove not reached by the largest modern flood, ¹³⁷Cs activity was measured in flood units dated to the Late Bronze Age. This indicates that a sediment-associated interpretation of ¹³⁷Cs derived from upstream sources cannot always be assumed for slackwater sediments deposited within rock alcoves. Local hydrogeological conditions may result in the presence of ¹³⁷Cs derived from local fallout and its subsequent mobility within the sedimentary profile.

1 INTRODUCTION

Palaeoflood hydrology, the reconstruction of the magnitude and frequency of large floods using geological evidence (Baker *et al.*, 2002), is a technique that has been applied in many regions of the world to improve flood risk estimation by lengthening the flood record beyond that of the instrumental gauging station data. The most useful sedimentary archives of palaeoflood events are sequences of slackwater flood deposits located within narrow gorge reaches (Baker and Kochel, 1988, Benito *et al.*, in press). Such sediments are deposited in zones of low energy flow conditions at the valley margin and represent the minimum water surface elevation reached during a flood event, the discharge of which can be estimated using hydraulic modelling techniques. In terms of cataloguing long-term flood records, and associated flood frequency, it is essential within the methodological framework to identify the number of individual flood units and obtain a chronology of deposition. The most common means of dating individual slackwater flood units is through radiocarbon dating of charcoal or other organic material deposited within the flood sediments. Radiocarbon dating, however, is inaccurate over the last few hundred years, therefore, other methods need to be applied to date recent flood deposits. The potential of the ¹³⁷Cs dating technique (Walling and He, 1997) for dating post-1955 slackwater flood sediments has been illustrated by Ely *et al* (1992) who recorded ¹³⁷Cs activity within

modern slackwater flood deposits of the San Francisco River, USA. The technique is of particular relevance within catchments such as the Llobregat where many gauging stations have only been operational over the last 50-60 years. ^{137}Cs dating can potentially be used to identify the number of slackwater flood units deposited during the instrumental period, with applications in: 1) flood frequency analysis, by ensuring that floods recorded in both the gauging data and sedimentary profiles are not repeated in the statistical analysis; and 2) identifying modern slackwater flood deposits and correlating them with their related discharges from the gauging station data to improve hydraulic model calibrations and, subsequently, the discharge estimates of pre-instrumental palaeofloods.

2 METHODOLOGY

Palaeoflood deposits were identified in rock alcoves located along two study reaches of the Llobregat River (Figure 1): Pont de Vilomara (1845 km²) and Monistrol de Montserrat (3370 km²). The number of individual flood units in each profile was determined by identifying sedimentological features such as clay layers representing the final stages of deposition during a flood; angular clast layers deposited between flood events; erosion surfaces and bioturbation (*Baker and Kochel, 1988, Benito et al., in press*). The minimum water surface elevations represented by the slackwater deposits were converted into discharge estimates by hydraulic modelling along the surveyed study reaches using the HEC-RAS one-dimensional model. The gauging station discharge record at Castellvell (the reference station for the Monistrol reach) is shown in Figure 3.

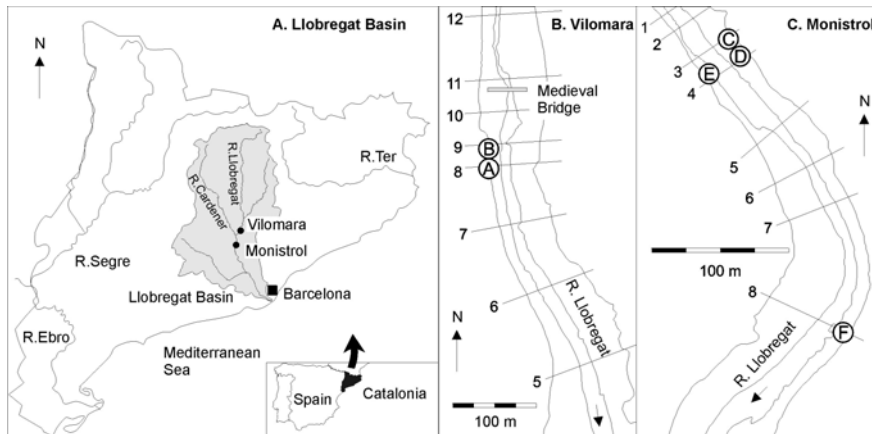


Figure 1. Catalonia and the Llobregat Basin (A). The upstream sections of the Vilomara (B) and Monistrol (C) study reaches, indicating the location of alcoves preserving slackwater flood deposits (lettered) and surveyed cross sections (numbered).

Radiocarbon dating was carried out by the ^{14}C laboratory of the Department of Geography at the University of Zurich (GIUZ). The dating itself was done by AMS (accelerator mass spectrometry) with the tandem accelerator of the Institute of Particle Physics at the Swiss Federal Institute of Technology, Zurich (ETH). Calibration of the radiocarbon dates was carried out using the CalibETH 1.5b (1991) programme of the Institute for Intermediate Energy Physics ETH Zürich, Switzerland, using the calibration curves of Stuiver and Pearson (1993).

The artificial radionuclide, ^{137}Cs , was first released into the atmosphere during 1950's nuclear bomb testing, the ^{137}Cs reaching the land surface by atmospheric fall-out. As the slackwater flood sediments at the study reaches are located within rock alcoves, protected from direct fall-out, it was assumed that the ^{137}Cs was sediment-associated and was redistributed with sediments mobilised from the upstream catchment. Sample ^{137}Cs activity was determined at the University of Exeter (School of Geography and Archaeology), using a p-type coaxial HPGe detector. Count times were typically 30000-50000 s, providing a precision of $\pm 10\%$ at the 95% confidence level. The ^{137}Cs dating results from the Llobregat River study reaches could be critically tested using the combined data of palaeoflood stratigraphy, radiocarbon dating, discharge estimation by hydraulic modelling and the instrumental discharge record.

3 RESULTS

3.1 Using ^{137}Cs to correlate recent slackwater flood sediments with the gauging station record

Figure 2 illustrates the stratigraphy, radiocarbon dating and ^{137}Cs data for Alcove E (Figure 1), a low elevation alcove of the Monistrol study reach. The minimum discharge estimates associated with the deposits within this alcove range from $150 \text{ m}^3 \text{ s}^{-1}$ at the base of the profile to $500 \text{ m}^3 \text{ s}^{-1}$ for the upper units. The site has preserved a total of 18 individual flood events. All three radiocarbon dates from the profile gave modern results illustrating that the sedimentary sequence, when only taking into account the radiocarbon dating evidence, was probably deposited over the last ca. 100-150 years.

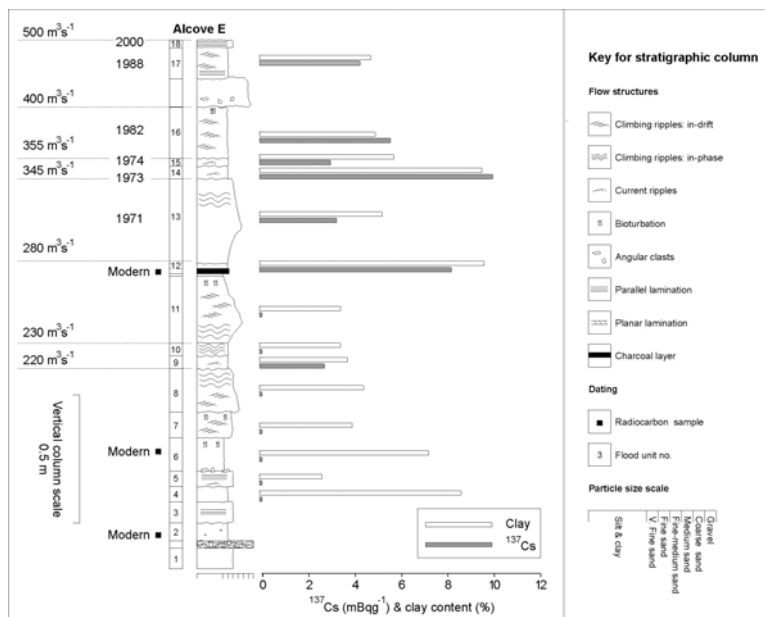


Figure 2. The flood stratigraphy of Alcove E and associated ^{137}Cs and clay content profiles. Minimum discharge estimates associated with selected flood units are illustrated and a potential flood chronology, from comparison with the gauging record, is hypothesised.

The use of ^{137}Cs dating, however, has enabled a more precise chronology of the profile to be determined. The first recorded ^{137}Cs occurs in unit E9 (Figure 2), with a concentration of 2.8 mBqg^{-1} , although no ^{137}Cs is present in the two overlying units, E10 and E11. The next flood containing ^{137}Cs is that of E12. The ^{137}Cs content of the sediments between floods E12 and E17 varies as a function of clay content (with a Spearman's Rank correlation coefficient, r_s , of 0.83, significant at the .05 level), with a peak value of 10.06 mBqg^{-1} occurring in flood unit 14, associated with a clay content of 9.6 %. The ^{137}Cs profile suggests that the 8 flood events deposited before the E9 event occurred prior to the mid to late 1950's, with events E9-17 occurring after this period.

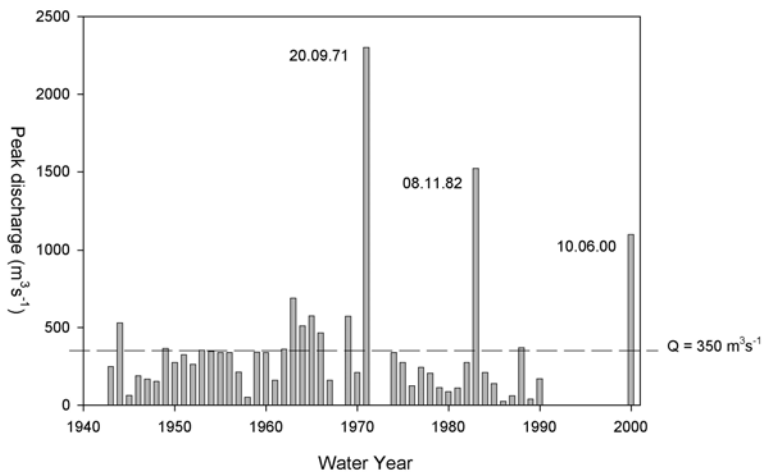


Figure 3. Annual peak instantaneous discharges recorded at Castellvell gauging station, the reference station for the Monistrol study reach. N.B. The floods of 1971 and 1988 were recorded as estimated minimum discharges.

Comparing the post-1955 gauging station data (Figure 3) with the flood stratigraphy, and associated minimum discharge estimates, an attempt has been made to date the individual units of the profile (Figure 2). This was successful for floods E13-18 as there were only a few flood events that exceeded the necessary threshold discharges required to deposit sediments within the alcove (illustrated using the discharge of $350 \text{ m}^3 \text{s}^{-1}$ in Figure 3). E18 is known to have been deposited by the June 2000 flood, as this occurred during the fieldwork campaign. Flood unit E13 is the thickest deposit (33 cm) within Alcove E and has been assigned to the flood of September 1971, the largest in the instrumental record. The two thin flood units E14 and E15 have been assigned to two floods that occurred during the same hydrological year (1973/74). The peak discharge of the 1973 event was $340 \text{ m}^3 \text{s}^{-1}$, very similar to the discharge threshold estimated as $350 \text{ m}^3 \text{s}^{-1}$ (Figure 2). Flood units E16 and E17 are believed to be the 1982 and 1988 floods, respectively. For the lower flood units, the correlation between the stratigraphic record and the gauging station is poor, as there are 10 floods between 1955 and 1971 that exceed $250 \text{ m}^3 \text{s}^{-1}$, with only 4 flood units preserved (E9-E12), indicating processes of deposition and erosion during successive floods. However, the deposition of E13 (in 1971) increased the threshold discharge necessary for further deposition from 280 to $345 \text{ m}^3 \text{s}^{-1}$. Since 1971 there has been a reduced frequency of floods greater than this threshold, enabling increased stabilisation of the

deposits, for example by vegetation growth. As a consequence the post-1971 flood record is better preserved.

3.2 Evidence for mobility of ^{137}Cs within slackwater flood deposits

Alcove A, at the Vilomara reach, contains 0.95 m of sediments that represent 8 individual flood units (Figure 4). Two radiocarbon dates of 853–776 cal. BC and 794–554 cal. BC were obtained from flood units A4 and A5, respectively, indicating a period of increased flood frequency during the Late Bronze Age period. The minimum estimated discharges relating to the elevations of these two flood events are ca. $4000\text{ m}^3\text{s}^{-1}$. As the upper 3 units were undated, samples were analysed for ^{137}Cs . Activity was detected in 6 of the 9 samples (with values of $0.7\text{--}2.6\text{ mBqg}^{-1}$), including samples from the radiocarbon dated A4 and A5 deposits. The peak flow of the 1971 flood was recorded as $1500\text{ m}^3\text{s}^{-1}$ at the Vilomara gauging station and estimated as $2300\text{ m}^3\text{s}^{-1}$ from modern slackwater flood deposits at Alcove B. The combined evidence from the flood stratigraphy, radiocarbon dating and hydraulic modelling, confirm that the 1971 event could not have reached Alcove A and, therefore, that the ^{137}Cs was not sediment-associated. The different behaviour of ^{137}Cs at the two alcoves discussed (A and E) appears to be dependent on the local hydrology of the alcoves. Alcove A is a small rock overhang, located on the valley margin, that is covered by a thin soil. Rainfall infiltrates rapidly through the fissured and permeable conglomerate rock and onto the surface of the fine sandy silt palaeoflood deposits. The maximum depth of ^{137}Cs in the profile is 0.40 m, indicating the mobility of ^{137}Cs , derived from rainwater, within the slackwater flood sediments. By contrast, the higher ^{137}Cs activity ($1.95\text{--}10.06\text{ mBqg}^{-1}$) measured in the Alcove E sediments, and the positive correlation between ^{137}Cs and clay content, suggest that the ^{137}Cs is held within the flood sediments. Alcove E is an alcove located at the base of a much thicker sequence of conglomerates, that appears to have protected the slackwater flood deposits from rapid infiltration of rainwater.

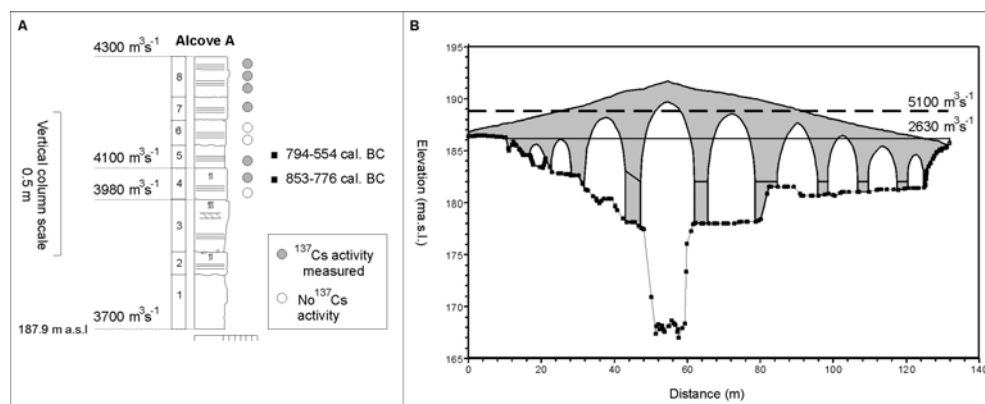


Figure 4. A. The flood stratigraphy of Alcove A, ^{137}Cs activity and minimum discharge estimates associated with selected flood units. See Figure 2 for stratigraphic key. B. Cross-section at the Vilomara Medieval Bridge illustrating the water surface elevations of the highest estimated minimum discharges of the 1971 flood ($2630\text{ m}^3\text{s}^{-1}$) and the Alcove A palaeofloods ($5100\text{ m}^3\text{s}^{-1}$).

4 CONCLUSIONS

^{137}Cs data has been presented from two sequences of slackwater flood deposits. At Alcove E, the dating technique has been successfully applied and illustrates the potential of the method in dating recent slackwater deposits in ungauged catchments or, in gauged rivers, in correlating recent slackwater flood deposits with the instrumental flood record. At Alcove A, however, ^{137}Cs activity measured in palaeoflood deposits dated to the Late Bronze Age, at a site where no modern flood sediments were deposited, illustrates that local hydrological conditions may permitting the receipt of direct ^{137}Cs fall-out, preventing a purely sediment-associated interpretation of ^{137}Cs derived from upstream sediments.

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7. DEVELOPING PROXY FLOOD RECORDS FROM SEDIMENT STACKS IN PALAEOCHANNELS: THE 'BLOODY INCHES' ON THE RIVER TAY, SCOTLAND

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ABSTRACT

Assessing the frequency of recent large floods in Scotland is hindered by short river records and non-homogenous flow series. Proxy flood records can be generated from sediment stacks in floodplain palaeochannels which steadily infill with silts during normal winter floods and fine sand during catastrophic floods. The 'Bloody Inches' (a meander cutoff on the lower River Tay, Scotland) has been infilling with flood deposits since c. 1763. Agricultural flood embankments near this site locally breach with flows $> 850 \text{ m}^3 \text{ s}^{-1}$ which introduce silts into the palaeochannel and extensively fail with flows $> 1200 \text{ m}^3 \text{ s}^{-1}$ which deposit fine sand. Repeated cores (up to 1.4 m in depth) at the site consistently reveal sand-rich flood units. In the upper core sections ^{137}Cs dating enables these to be correlated with floods $> 1200 \text{ m}^3 \text{ s}^{-1}$ in the post-1950 discharge record at the Caputh gauging station 5 km upstream. Sand units in the lower part of the profile are correlated with floods from 1780 onwards using a ^{210}Pb -based chronology and independently supported by a detailed record of flood marks inscribed on Smeaton's Bridge in Perth, 15 km downstream. This ability to recover proxy flood records from sediment stacks in floodplain palaeochannels provides a new tool for assessing the return periods of recent major floods in Scotland and useful natural analogues for assessing flood risks under the warmer wetter regimes predicted by climate modellers for the 2050s.

1 INTRODUCTION

The late 1980s and 1990s produced the wettest period in Scotland since the 1750s and, on many rivers, their highest recorded flows (*Black and Burns*, 2002). This is consistent with the warmer and wetter Scotland predicted by climate modellers for the 2050s – a decade which may also experience a heightened flood risk (*Werritty et al.*, 2002). Such predictions, however, remain uncertain because of difficulties in modelling future extreme precipitation from GCMs, downscaling the results to the basin scale and converting these estimates into peak instantaneous flows (*Werritty*, 2002). Given these uncertainties, it is important to determine the frequencies of the floods in the late 1980s and 90s as potential analogues of what might occur in a wetter and warmer Scotland. But estimating return periods for these recent floods is difficult due to short instrumental records (rarely > 50 years) and uncertainties from sampling “flood poor” and “flood rich” periods (*Werritty et al.*, 2002). One potential solution is to assemble historic flood chronologies which extend the instrumental record back several centuries (*MacDonald et al.*, 2002). Another approach

– the one adopted here – is to assemble proxy flood records from sediment archives held in floodplains, an approach pioneered by Knox in southwest Wisconsin (see *Knox 1999* for recent review).

2 RECONSTRUCTING PROXY FLOOD RECORDS FROM FLOODPLAIN SEDIMENT ARCHIVES

Many Scottish floodplains display well-developed palaeochannels which evolve as an active river migrates across its floodplain leaving behind abandoned cutoffs. These former channels then become sediment sinks, slowly infilling with overbank sediments until eventually they become annealed into the floodplain. Coring these sedimentary fills typically yields a basal gravel (denoting the bed of the former channel) with alternating silty and sandy facies within the sediment stack. The former record frequent, moderately-sized overbank floods during which only silts and clays are transported in suspension across the floodplain. The latter record the transport of fine- to medium-sands across the floodplain during rare, large floods followed by deposition in palaeochannels and elsewhere (*Nicholas & Walling, 1997*). Thus the sediment stack represents a flood archive with the sandy facies registering the occurrence of rare, large floods. If individual sandy facies can be dated, it should be possible to generate a proxy record of flood frequency extending back to when the palaeochannel was cutoff from the main channel.

This relatively simple conceptualisation of proxy flood archives being contained in palaeochannel sediment stacks assumes a steady upstream sediment supply and stable local floodplain hydraulics throughout the record. Given the timescales involved, it is unlikely that either assumption will be fully met. Land-use change since the 1750s in both uplands and lowlands (deforestation, draining wetlands, channelisation, the development of hydro-electric power) have modified sediment fluxes typically resulting in reduced sediment yields in the lower reaches of Scotland's major rivers (*Gilvear & Winterbottom, 1992*). However, providing sediment-rich overbank flows still reach specific palaeochannels, this decline can be documented and incorporated into the reconstruction of the proxy flood record. Changes in local floodplain hydraulics also arise following 200 years of river engineering and the construction of agricultural flood embankments usually to protect against the 5-10 year flood. Again these can be incorporated into the proxy flood record providing the location and history of embankment construction and maintenance is known. Also implicit in the above conceptualisation is the assumption that the floodplain is not locally subject to vertical change (aggradation or degradation) which would alter the threshold for overbank flows.

A reconnaissance of upland and lowland valleys has yielded many sites with suitable palaeochannels where reconstruction of proxy flood records might be attempted. Coring of palaeochannels alongside the Derry Burn (*McEwen, 1997*), the River Clyde and Medwin Water (*Rowan et al., 1999*), the lower River Earn and the 'Bloody Inches' on the lower River Tay (*Paine et al., 2002*) have all revealed the expected alternation of silty and sandy facies within the channel fill. In this paper we report results from the 'Bloody Inches' on the lower River Tay.

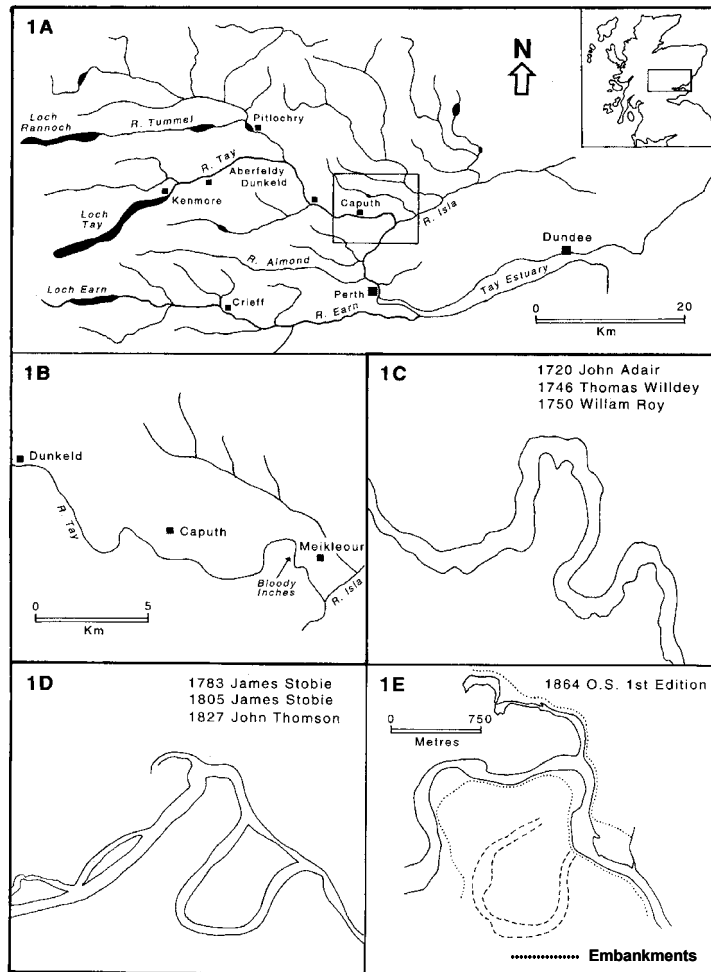


Figure 1: (A) Geographical location and the River Tay basin; (B) the study area; (C) – (E) development of the 'Bloody Inches' 1720-1864 from series of large scale estate plans Ordnance Survey maps. Maps in (C) and (D) all record the channel pattern shown.

3 RECONSTRUCTING THE FLOOD RECORD AT THE 'BLOODY INCHES' ON THE RIVER TAY

In order to test the conceptual model presented in the previous section, a site with a well-defined evolution, long instrumental record and rich independent historical flood chronology was required. A site well-suited for this purpose is the 'Bloody Inches': the name given to a mid nineteenth century palaeochannel adjacent to the River Tay, 5 km downstream of the Caputh gauging station and about 15 km upstream of Perth, a town frequently damaged by floods (Figure 1A-B). The evolution of the site is recorded in seven

maps between 1720 and 1864 (Figure 1C-E) and the history of the construction of the agricultural flood embankments is reasonably well documented. Given a flow record back to 1951, the conceptual model was tested by dating the sandy facies in the upper part of the sediment stack using ^{137}Cs and checking by reference to known major floods in the instrumental record. The lower part of the sediment stack was dated by ^{210}Pb and flood units correlated against a detailed epigraphic record of flood levels on Smeaton's Bridge in Perth from 1814.

3.1 The River Tay drainage basin and study site

The River Tay (drainage area of 3210 km² at Caputh) has an average flow at Perth of 160 m³s⁻¹ (the highest of any UK river) and a flood history that dates back to 1210. Low evapotranspiration, thin soils and impermeable substrates combine to produce high runoff ratios although the resulting flows and sediment fluxes are moderated by significant storage in Lochs Rannoch, Tummel and Tay. Hydroelectric schemes constructed from the late 1930s to the 1950s control the outflows from Lochs Tummel and Rannoch along with flows down the River Garry with the result that 62% of the drainage basin now reports regulated flows. The 'Bloody Inches' comprises a large oxbow lake whose separation from the main channel of the Tay is documented in a series of maps spanning 1720 to 1864 (Figure 1C-E). Although the planimetric accuracy of the eighteenth century maps may be questioned, the overall channel pattern is consistent and reliable. The date of cutoff of c. 1763 was obtained from historical archives (*Statistical Account of Scotland*, 1845) and shown to be the result of a major flood. Flood embankments were in place by 1831 and a programme of modification and raising has continued to the present day. *Gilvear & Black* (1999) report local failure of these embankments at flows > 850 m³s⁻¹ and widespread failure > 1200 m³s⁻¹; the latter representing the threshold for conveyance of clastic sediment to the apex of the 'Bloody Inches' cutoff (c.f. *Paine et al.*, 2002).

3.2 Data capture: field and laboratory methods

Sediment cores, typically 1.4 m deep, were obtained at 8 sites within the apex of the 'Bloody Inches' meander using a vibro-corer, 1 m gouge auger and a 0.5 m Russian auger. Within the palaeochannel fill the gravel/sand boundary denotes its effective separation from the main channel. Each core was logged, discrete sedimentological units identified and either sampled at regular intervals or variously determined by their stratigraphy. Following drying and gentle disaggregation, the granulometry of each core was determined using a Coulter LS230 laser granulometer on the chemically-dispersed mineral fraction. Radiometric dating (^{137}Cs and ^{210}Pb) was undertaken by gamma spectroscopy using an Ortec Lo-Ax high purity germanium detector housed in a copper lined lead shield and typical count times of 86,000 seconds. ^{137}Cs activity provides the basis for dating flood facies back to the mid 1950s, whereas ^{210}Pb activity extends the dating control back c. 150 years.

3.3 Results

Figure 2 illustrates a simple representation of the channel fill sequence obtained from Core T5 revealing four distinct phases in the aggradation history of the site. The 1780-1830 unit overlying the channel lag largely comprises medium to coarse sands (> 250 μm). The period 1830-1870 contains alternating units of silts, organic matter and sandy facies (fine to medium sands 125-500 μm). The period 1870-1900 features a marked increase in the silt fraction, and from 1900 to present the fill is predominantly silty, organic rich with

occasional discrete sandy units, with a total absence of the $>250\ \mu\text{m}$ fraction after 1960. These gross changes in sediment character reflect catchment scale changes in runoff and sediment delivery related to land use change and hydro-power regulation effects (*Paine et al.*, 2002), and phases of embankment enlargement from 1830 until the present hydraulic configuration was completed.

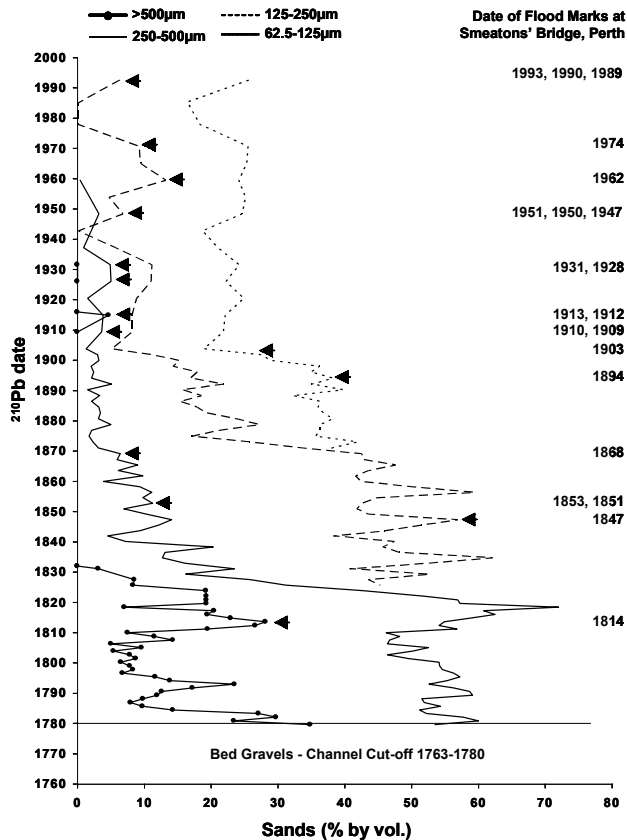


Figure 2: Granulometric analysis of core T5 at the 'Bloody Inches'.

The Caputh river flow record itemises the 25 floods which have overtopped the embankments since 1950. The fact that considerably fewer floods can be distinguished in the core indicates that spillage alone is insufficient to deposit recognizable flood facies. Those events which are recognisable, e.g. 1993 and 1990 with return periods of 65 and 45 years respectively, represent a sub-set of events with peak flows $> 1200\ \text{m}^3\text{s}^{-1}$, which appears to represent a threshold for widespread failure of the flood embankments in the modern period (c.f. *Gilvear and Black*, 1999). By contrast, lower sections of the core contain evidence of many more event horizons e.g. the 70 year period between 1830-1900 contains at least 12 major flood units, although only five of these are recorded at Smeaton's Bridge. The significance of this observation is that while flood frequency can be derived, because of uncertainties relating to the size, extent and condition of the embankments during this period it is not possible, at present, to derive a comparable magnitude threshold.

The earliest period 1780-1830 contains a large number of floods, the most notable (in 1814) being the largest flood recorded at Smeaton's Bridge. It seems likely that this frequent inundation of locally productive farmland stimulated the first major phase of embankment construction in the early 1830s.

4 DISCUSSION AND CONCLUSIONS

Analysis of a sediment core from the 'Bloody Inches' on the lower River Tay has yielded a sediment archive of datable flood facies back to the 1780s, many independently supported from flood levels on Smeaton's Bridge. The upper portion of the core, dated radiometrically and tied to the post-1950 gauging record, indicated that an event threshold of $1200 \text{ m}^3 \text{ s}^{-1}$ was required before a flood unit could be distinguished. Multiple flood units emplaced prior to the last phase of embankment upgrading reflect different and, most likely, lower deposition thresholds. The pattern of switching between "flood rich" and "flood poor" periods in the recent past is echoed throughout the sediment core. Radiometric dating of palaeochannel deposits at other sites holds the prospect of substantially extending our knowledge of flood frequencies on many of Scotland's rivers. Such proxy flood records would then enable the recent floods in the late 1980s and 1990s to be placed in their correct historical context.

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8. PALEOFLOOD RECONSTRUCTION AT ILLGRABEN TORRENT (SWITZERLAND): A CURRENT NEED FOR EVENT FREQUENCY ESTIMATION

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ABSTRACT

The presentation of this case study will allow us to enlighten the problem encountered in the analysis of floods and paleofloods involving very concentrated sediment transport (i.e. debris flows). In order to date debris flow events we use several techniques: dendrochronology, stratigraphy analysis, C^{14} , and historical records. The concerned creek is the Illgraben. It built a big alluvial fan in the upper Rhône valley. This fan has an approximate age of 17,000 years but our study only concentrate on the last millennium. Due to non-newtonian and transitory characteristics of the flow classic hydraulic computation could not be done. The main concern of this paper is to show how frequency is not only related to hydrological parameter but also to geological and anthropological events.

1 INTRODUCTION

The Illgraben's creek is well known for flash floods in the Walliser Alps, southern Switzerland (Figure 1). The creek reaches the Rhône's valley floor. A settlement (*la Souste*) was built on the fan. A regional road, high tension wires, a hydropower canal (and soon a motorway) are crossing the Illgraben's creek. Almost every year a few flash floods with high suspended sediment content have been observed. The nature of these phenomenon ranges from hyperconcentrated flows to debris flows. The total catchment's area is 10 km² but only 3 km² are intensely involved in sediment supply.

During the XXth century more than 3 events of over 100'000 m³ were reported. During years without high magnitude events it is assumed that 100,000 to 200,000 m³ of sediments are eroded from the catchments. It induces productivity rates from 25,000 to 50,000 m³/km²/a. These very high rates have several implications for risk management in this area.

The public authorities needed a magnitude-frequency analysis to be carried out. Particularities of these phenomena (transitory, non-newtonian, 3D deposits) did not allow us to use classical hydraulic and hydrological approaches to identify their magnitude and frequency. For this reason we based our work on the global dynamic of the torrent system.

V.R.Thorndycraft, G. Benito, M. Barriendos and M.C. Llasat (2003). Palaeofloods, Historical Floods and Climatic Variability: Applications in Flood Risk Assessment (Proceedings of the PHEFRA Workshop, Barcelona, 16-19th October, 2002).

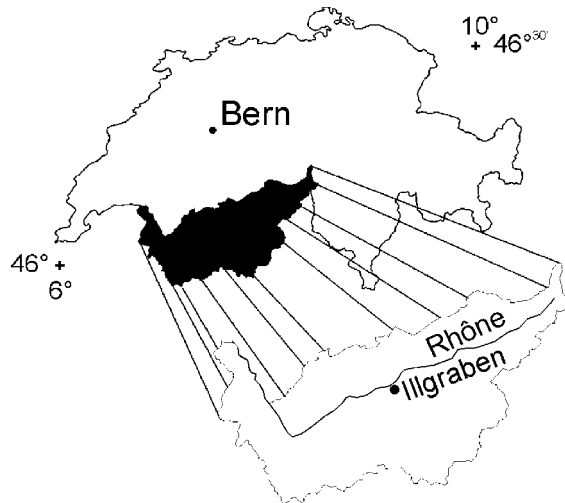


Figure 1. Study area location

2 METHODS USED

Four main sources were used to cover the wide range of time to be investigated. All of them bring us specific information on part of the timescale. We used:

- Dendrochronology.
- Stratigraphy analysis.
- Radiocarbon (C^{14}) dating.
- Historical records.

Dendrochronology allowed us to date flooding terraces in the current overbank channel and on the inactive part of the alluvial fan (providing information in plan). Stratigraphy analysis and C^{14} datation were employed to date palaeosoils in eroded banks (providing vertical, depth information) and historical records gave additional information on the dynamics of the system (but not more because there were only a few records).

3 RESULTS OF DATATION

3.1 Dendrochronology

This method gave us two results at different levels of confidence. Firstly, with a good accuracy, flooding terraces could be dated in the overbank channel. Secondly, with a low level of confidence, old trees on the currently inactive part of the alluvial fan could be dated but without knowing the age of their substratum.

In the overbank channel we produced a map of terrace ages, which cover a period from today to 1872 (i.e. back to 128 years).

On the inactive part of the alluvial fan, datation of trees gives an age of ~100 years. However the forest has been exploited there and both historical records and the ground surface morphology does not show any evidence of major change over the last two centuries.

3.2 Stratigraphy analysis & C¹⁴ datation

During the previous survey - and due to the current erosion trend of the torrent that makes a deep trench in the fan - we discovered paleosoils. Organic matter that is contained inside them and their organization in the field help us to have an idea of the past dynamic of the watershed. Within the 20 m long section exposed by the erosion we found 4 paleosoils. Between these marks different layers of debris flow deposits were observed. Due to financial constraints we were only able to date 2 soils and 1 trunk. Ages range from the middle of the XIIIth to the middle of the XIVth century. Table 1 summarizes the results. The determination of the age, the preparation and the datation of samples were done by the radiocarbon laboratories of Institut of Physics at Bern University and the Institute of Particle Physics of the ETH Zürich.

Sample	Calibrated age (AD)	Depth under current ground
Soil sample A1	1161-1301	5 m
Soil sample D4	1297-1412	2 m
Trunk	1441-1474	7 m with no soil over it

Table 1. Results of the C¹⁴ datation on organic matter sampled from the paleosoil and the trunk.

The spatial correlation of levels does not respect the chronological order. We are to be aware of the lack of 3D information. Indeed we have only a reference from the top (*i.e.* a relative reference) and not a reference from the bottom (*i.e.* an absolute reference). It signifies that the quite homogeneous diamict that burry dated signs could be a consequence of overbank flooding (in this case paleosoils are conserved) or from deposits in an ancient channel (in this case paleosoils are absent). The only interpretation of these results is that major changes occur since this period.

3.3 Historical records

Due to the environment of the *Rhône's* valley (swamp, frequent floods, etc.) all settlements were placed a little bit on the flank of the valley. This implies that only a few historical data are available on the alluvial fan. One indication is the name of *la Souste* itself. It was used in the Swiss Alps to mention a place of goods storage before difficult roads. The first reference of this location goes back to the XVth century at least. If it could be related to the commercial road of the *Gemmi*, it seems obvious that this place was used to prepare for the passage of the fan too. The second indication is that, in the same period, the way to the high mountain pastures of the people of *Loèche* (the settlement that overhangs *la Souste* in the *Rhône's* valley) passed trough the Illgraben's canyon in places that are no longer reachable due to present day intense erosion. The third indication is that there are no records of flooding outside the overbank channel since the beginning of the XIXth century (when the forest was already exploited).

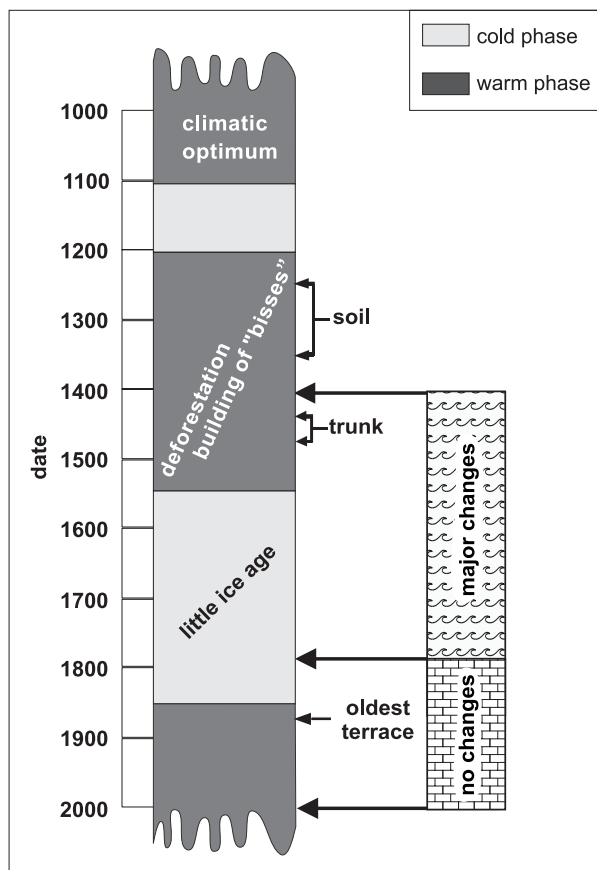


Figure 2. Comparison of the dated evidences with the well-known climatic period of the last millennium.

4 INTERPRETATION

In the studied area post-glacial history began 17'000 years B.P. with the *Rhône's* glacier retreat. Geological evidence (the large rock avalanche of *Sierre*, Burri 1955) allows us to estimate the first evidence of sedimentary activity of the *Illgraben's* creek around 10'000 years B.P.

Data in our possession only cover the last millennium. We will concentrate on this period. During these thousand years 5 different climatic phases are described (Zryd, 2001). There phases are: a warm phase called “the climatic optimum of the year thousand”; a small refreshing phase during the XIIth century; a warm phase from 1200 to 1550; the Little Ice Age from 1550 to 1850; and the current warming phase.

In Figure 2 we present our dated points in adjacent to the climatic evolution. On the basis of the information in our possession, this figure shows that major changes occurred at the location analysed in between the middle of the warm phase corresponding to a new and intense exploitation of the territory and the middle of the Little Ice Age. We see that transitions between periods do not correspond with possible upsurge of flooding on the fan. It is difficult to separate effect due only to the climate or to the impact of anthropologic changes.

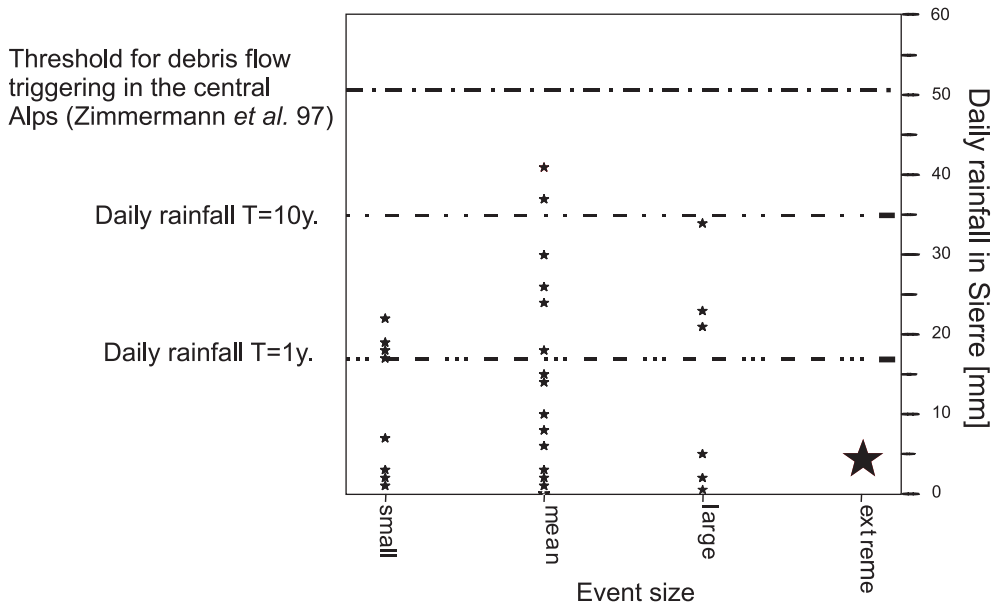


Figure 3. Comparison of the rainfall in Siere and the magnitude of event in Illgraben (adapted from Zimmermann 2000)

Comparing well documented events of the last decades (from 1932 to 2000) to the rainfall in *Siere* (a town located 4 km away) no trend in the rainfall-magnitude relation appears (cf. Figure 3). Furthermore the largest recorded event (in 1961) occurs with very low rainfall. This poor interpretative issue urges us to go into more detail of the dynamic of the whole system. Figure 4 presents the evolution of the system in 4 steps:

1. Before human influence the main alluvial fan (*Finge's fan*) noted **a** on the picture, was fed by two tributaries: the *Illgraben* and the *Illwasser*. The *Illwasser* built a smaller fan at the confluence of the 2 creeks (fan **b**).
2. The mention of the settlement of *la Souste* corresponds to the beginning of the human impact in the region during the XIVth century (see Section 3.3). Many centuries later, in 1942, the retention dam of *Illsee* (noted **c** on the picture) was built on the *Illwasser*, changing the rate of sediment supply at the confluence (fan **b**). This provoked erosion of the bed at this location. In 1945 wooden check dams were constructed on the main fan (noted **e**). Later a power dam (noted **d**) was built on the *Rhône's* river causing change of hydraulic conditions at their confluence.
3. In 1961 a severe rock avalanche occurred in the upper part of the watershed (*Lichtenhan* 1971, *Eisbacher & Clague*, 1984). The scarp (noted **f**) had a volume of 5 millions m³. This event provoked a deposit in axis of the *Illgraben's* valley (noted **g**). This deposit dammed a lateral channel of the *Illgraben's* creek, this create a small lake (the extreme debris flow of 1961 triggered with little rain was probably due to the sudden release of this lake). To prevent a sudden break of the natural dam, a big check dam was set up in 1971 (noted **h**). Following the rock avalanche we observe an upsurge of debris flows on the main fan (approximately 3-4 a year). This fact can be

linked with the availability of sediment in the upper part of the valley along the deposit.

4. Recently in May 2001 a new small rock avalanche dammed the channel (noted i). Since then no debris flow occurred until august 2002. The first observations showed us that not only the frequency but also the rheology of debris flows have changed. Indeed during bad weather of November 2002 in Switzerland the debris flow reached only the *Rhône's* river and stopped on the fan. This created a new major change in the channel morphology.

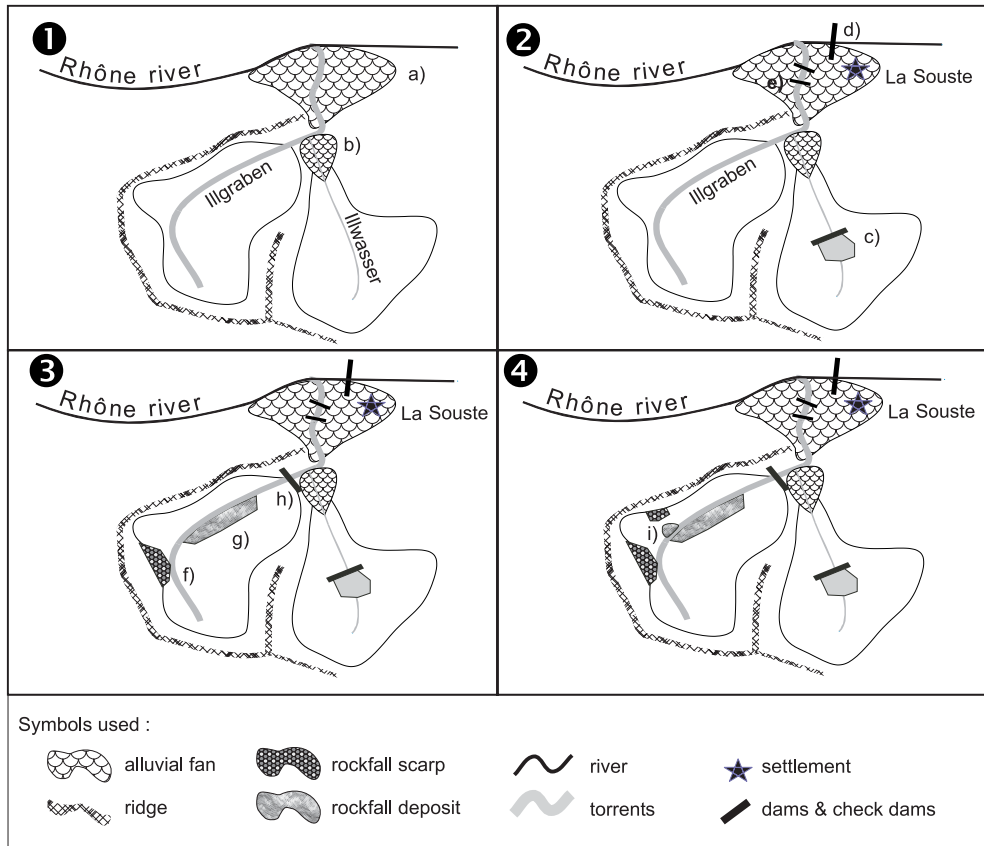


Figure 4. Dynamic reconstruction of the system formed by the Illgraben and its tributaries and effluent.

5 CONCLUSIONS

Prediction of “magnitude-frequency” characteristics of solid transport events in such torrents is impossible if geological or anthropological events are not taken into account (rock avalanche, fan formation, deforestation, dams, etc.). It cannot be directly related to

climate change. Further, even if it is not totally sediment-constrained, this torrent shows poor correlation with rainfall events.

This study shows how a careful analysis of the system's dynamic helps to explain changes of the "magnitude-frequency" relationship through the time. However it only gives a qualitative trend and more work is needed to get to a quantitative analysis.

This study shows that analysis of all debris flow events could be helpful for "magnitude-frequency" reconstruction of geological events too.

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9. HISTORICAL FLOOD EVIDENCE USING GEOMORPHOLOGICAL AND DENDROCHRONOLOGICAL RECORDS, SUDETES MOUNTAINS, CENTRAL EUROPE

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ABSTRACT

The Sudetes are a mid-mountain range located in the temperate climatic zone of Central Europe. Deep valley sides are covered with a thick mantle of periglacial regolith. Migrating cyclones cause intensive rainstorms and floods here. Geomorphological and sedimentological traces of a previous large flood have been found in the upper course of the Bila Opava valley floor, which drains the northern slope of the Hruby Jeseník massif, 1000-1400 m a. s. l. (Praded – 1491 m a. s. l.). Dendrochronological investigation has shown that this large flood took place around the turn of the 20th century. Meteorological records found in the archives have confirmed that extremely heavy precipitation occurred in the headwater area of the Bila Opava on 9 July 1903. The periglacial regolith covering the steep, deforested slopes of the valley were the source of coarse-grained clastic material supplied into the Bila Opava river-bed.

1 LOCATION AND PROBLEM

The Sudetes are a mid-mountain range located in the temperate climatic zone of Central Europe (Figure 1). The average elevation of the Hruby Jeseník massif, located within the Eastern Sudetes, is 1000-1400 m a. s. l. (Praded – 1491 m a. s. l.). Along the upper course of the Bila Opava drainage basin, the Hruby Jeseník massif consists primarily of Devonian orthogneiss, locally migmatites and – in the upper parts – fine and medium-grained paragneiss (Sawicki 1995). During the cold Pleistocene periods, the northern foothills of the Sudetes were probably twice covered by the Scandinavian ice sheet. During the last glaciation (the Vistulian) the ice sheet margin reached within around 200 km of the Hruby Jeseník massif. This created conditions conducive to intensive mechanical weathering. Thick regolith covers of varied lithology and age were formed during the cold Pleistocene periods.

In its upper course, the Bila Opava valley is cut to 200-250 m into the eastern face of the Praded massif. The inclination of its slopes reaches 500 m/km in some places. There is periglacial slope cover on the valley sides, formed by block fields on the outcrops of quartzites rocks with fine grained matrix in the gneiss and mica schist zones. There are numerous waterfalls on the quartz vein outcrops in the upper course of the Bila Opava channel. Further down the valley its longitudinal slope exceeds 60 m/km and the width of the valley floor reaches 60 to 80 metres. Big boulders are deposited here, forming a typically braided pattern overgrown with an old spruce forest (Figure 2).

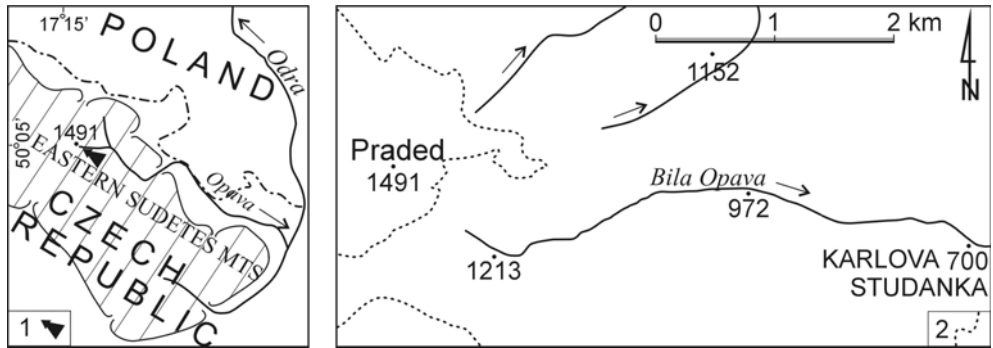


Figure 1. The study area on the background of Sudetes Mts., Central Europe. 1- Bila Opava valley, 2- upper tree line.

A



Figure 2. The boulders deposited during big flood in Bila Opava valley infilling an overflow channel (A) and present river channel (B)

The braided pattern found on the valley floor indicates the occurrence of large floods in the past, which caused the accumulation of these coarse alluvia. This paper attempts to investigate the reasons for these phenomena and the time when they occurred.

2 THE VALLEY FLOOR TOPOGRAPHY

The exquisitely preserved braided river pattern in the valley section under examination consists of a group of boulder palaeo-bars. The majority of them formed as longitudinal central bars with their lee slopes running diagonally to the valley axis (Figure 3). In many places the edges of the palaeo-bars are dissected with overflow channels. Residual boulders with a diameter of up to 2 metres (Figure 2A) are very often found in these channels and also below the undercuts on their edges. The undercuts of these coarse alluvia indicate that palaeo-bars are mainly composed of boulders up to 1 metre in diameter, well imbricated in many places. The width of the present-day river channel reaches several dozen metres. Its longitudinal slope is not uniform. There are rocky controlled sections along the course of the river channel and there are rapids and small waterfalls in the area where quartz vein outcrops are present. There are boulders of varying diameter in other places on the bottom of the river-bed, the majority of them well imbricated (Figure 2B). The river-bed is incised up to 2 metres below the level of the palaeochannels separating the palaeo-bars. This indicates the long-term horizontal stability of the river bed and its tendency to vertical erosion.

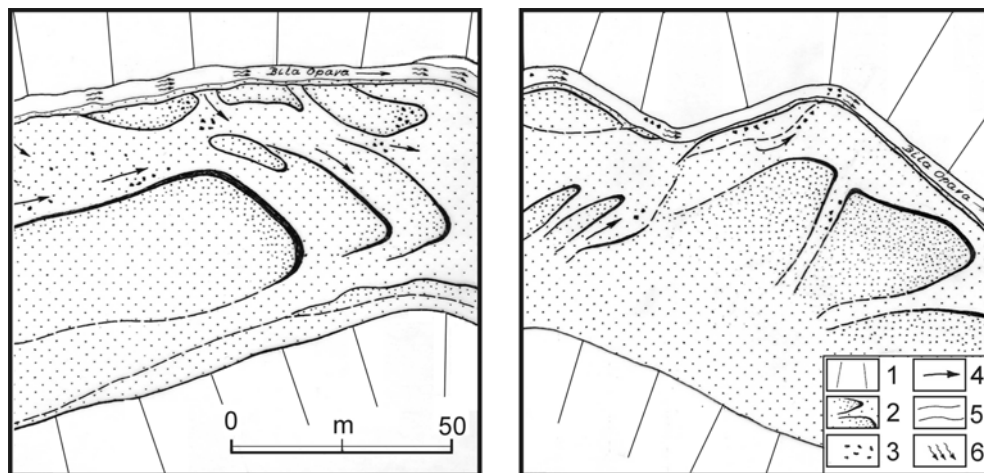


Figure 3. The sub-fossil braided river pattern in the upper course of Bila Opava valley; Eastern Sudetes Mts. 1-valledry slopes, 2-sub-fossil braided river pattern, 3- residual boulders, 4- palaeo-flows, 5- present-day channel, 6- rapids.

The petrographic composition of the clasts reflects the geological structure of the valley slopes of this section. The residual boulders of over 1 m in diameter are dominated by quartz, whereas the smaller ones, over 30 cm in diameter, are dominated by quartzite (41%) and gneiss (40%), while the finer clasts are composed primarily of gneiss (up to 60%) and quartzites. There is also a small admixture of mica schist.

The presented fossil braided river pattern in the upper course of the Bila Opava river points to the occurrence of very large flood/floods in this part of the Eastern Sudetes, with enough energy to transport and deposit very substantial quantities of coarse debris.

3 THE AGE OF THE EXTREME FLOOD

The natural upper tree line in the headwater area of the Bila Opava, in the vicinity of the Praded plateau (1499 m a. s. l.), occurs at the elevation of about 1400-1430 m a. s. l. It is formed by spruce forests (*Picea*) but in some places there are mountain pine (*Pinus mughus*) bushes above. There are natural communities of spruce, unaffected by human activity, in the upper course of the drainage basin, usually above 1000 m a.s.l., also occurring on steep rocky slopes and in other inaccessible places. On lower sections of slopes the artificially introduced even-aged spruce monocultures dominate. Tree clearance has been practiced in the mountain section of the Bila Opava drainage basin since the Middle Ages – originally for charcoal production for the copper smelters that existed here. Total tree clearance on vast slope areas has probably been practiced here at least since the 19th century. This means that until new trees had been planted, there was no compact forest over large areas of slope.

Tree-ring growth increment analysis indicates that the oldest spruce growing on this braided river pattern may be more than 75 years old (Figure 4). Taking into account the time required for the formation of the initial soil and the succession of pioneer vegetation, the spruce succeeded here around the turn of the 20th century. This leads to the assumption that the large flood which caused the braided river pattern formation in the valley section under research occurred at the turn of the 20th century.

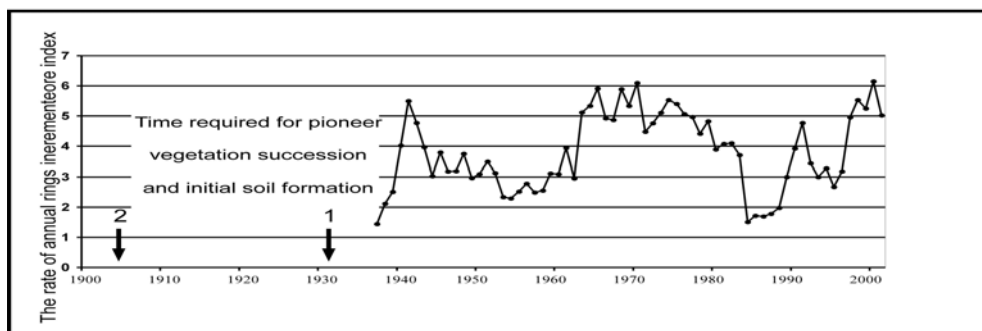


Figure 4. The tree-ring grown increment (1.5 m above ground level) of spruce overgrowing the sub-fossil bars in the Bila Opava valley; 1- supposed young spruce germination; 2- boulder bar deposition /flood occurrence.

The Hruby Jeseník massif receives about 1500 mm of precipitation per year. The major part of intensive precipitation is linked to synoptic situations, in which the cyclones from central, eastern or north-easterly directions in Europe create favourable conditions for continuous heavy precipitation (Stekl et al. 2001). The probable maximum precipitation in such situations reaches 300 mm/2 hours (Stekl et al. 2001). Such heavy rainfalls trigger large floods, which occurred several times in the Hruby Jeseník massif and its vicinity at the turn of the 20th century: namely in 1897, 1899, 1900, 1901, 1902, 1903 and 1906 (Polah and Gaba 1998). The largest flood occurred in June 1903 and was caused by precipitation of an amount that has never been recorded since. On 9 July 1903 the existing rainfall gauge stations in the northern part of the massif, situated at 310-775 m a.s.l., received 200-240 mm of precipitation. The higher, central part of the massif, where the headwater area of the Bila Opava drainage basin is located, probably received much more

precipitation. This heavy rainfall generated a flood wave that was sufficient to transport and deposit very coarse material, forming the braided river pattern.

4 THE SOURCE OF SEDIMENT

As it has already been stated, the slopes of the Hruby Jeseník massif are covered by a mantle of periglacial regolith. Some of them, especially the ones located on mica schist outcrops, are prone to liquefy when excessively saturated with water. Debris flows and/or related phenomena, known as “mura” are generated in such circumstances, especially above the upper tree line or on the steep slopes of deeply incised valleys (Migon *et al.* 2002). These debris flows in the Hruby Jeseník massif can be over 100 metres wide, 800 metres long and several metres thick (Gaba 1992). There are distinct traces of landslide niches or debris flow tracks on the steep slopes of the Bila Opava valley, especially on the southern slope of the valley section under consideration. A uniform age spruce forest has currently grown on this slope. In the lower part of the slopes the oldest trees are around 60-65 years old, which indicates recent afforestation following earlier deforestation. A photograph of the Bila Opava valley near Karlova Studanka taken before 1939 (*Grossdeutschland...* 1939) confirms the presence of large deforested slopes there at that time. This gives proof that the debris flows generated on steep valley slopes were the primary source of material forming the boulder bars in the Bila Opava valley section under research.

The superposition of the extreme weather phenomena of July 1903 and the human-induced clearance of a large area of mountain slopes caused the landslides or debris flows, which supplied the upper course of the Bila Opava with large quantities of debris and regolith. Already entrained during the flood, this material was redeposited, forming the braided river pattern.

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10. RIVER-RESPONSE AND TERRACE AGGRADATION IN THE MEDITERRANEAN IBERIAN PENINSULA DURING HISTORICAL TIMES

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ABSTRACT

Mediterranean fluvial environments have responded sensitively to past changes in climate, physiographic conditions and human activity. Chronosequences of river terraces and alluvial deposits were established using morphologic, sedimentological and pedologic criteria, ^{14}C - and ^{210}Pb -dating techniques, historical data and pottery fragments. The objective of this study addresses the fluvial dynamic of several river systems focusing on the Vera basin and the lower Penedes basin over the last 1600 years. The correlation between 13 catchments of Southwest, Southeast and Northeast Spain, studied by this research and by various authors, shows that fluvial activity increased during the cooler Holocene climate events such as the Early Medieval Ice Advance (6th – 10th century) and the Little Ice Age (15th – 19th century). In contrast, fluvial dynamics during the Medieval Climate Optimum were insignificant.

1 INTRODUCTION

Paleofloods and their related morphological processes are the result of climate variability and specific geo-ecological conditions and changes in the past. The natural records of these processes, including fluvial terraces, floodplains, colluvia, paludal and slope deposits and paleosols, can be assessed by geomorphological, sedimentological, pedological and chronostratigraphical methods. The objective of this study addresses the fluvial environments of several Mediterranean river systems focusing on the Vera basin in Southeast Spain and the lower Penedes basin in Northeast Spain. A crucial question is whether the river dynamics during historical times have been sensitive to centennial and decennial climate variability or whether they have been conditioned by the influence of human land-use. A large number of local studies of individual river systems exist for the Mediterranean Basin. However, systematic regional assessment of Holocene river dynamics or supra-regional overviews is rare. Regional studies undertaken by Brückner (1986) in Italy and Van Andel *et al.* (1990) in Greece show that regional and local river dynamics are much more complex than the stratigraphical subdivision of valley floors in “older” and “younger fill” deposits, proposed by the pioneer studies of Vita-Finzi (1969). The present study aims to integrate the data obtained on paleo-fluvial environments from the Vera and Penedes basin with other case studies, and to establish a fluvial chronostratigraphy of the Mediterranean Iberian Peninsula over the last 1600 years.

2 MATERIALS AND METHODS

Holocene fluvial landforms of the Vera and the Penedes basin were mapped by aerial photograph survey and fieldwork. Sedimentological descriptions were carried out for fluvial and paludal sediments. Samples and artifacts were collected from several geological sections and their magnetic susceptibility was measured. Soil description and geochemical and micromorphological analysis were carried out to assess the Holocene and late Quaternary soil development. The chronology of the river terrace sequences was determined from ^{14}C and U/Th-dating as well as from artifacts. In addition, ^{210}Pb -dating, undertaken in floodplain deposits, was calculated following the Constant Initial Concentration model (CIC).

3 SITE DESCRIPTION

The Vera basin is located at the eastern margin of the Betic ranges in Southeast Spain, the driest region in Europe. The semi-desert characterised by sparse vegetation cover, records today between 200 to 250 mm/yr total annual precipitation. Three mayor river systems cross the Vera basin from the west to the Mediterranean Sea in the east: the Almanzora river in the north, the Antas river in the middle and the Aguas river in the south. The northern study site, the lower Penedes basin, is located at the western end of the Catalan Coastal Range. The research focuses on the ephemeral catchments of the Riera de la Bisbal, Torrent del Lluç and Torrent de la Grallera. Annual precipitation at 500 mm/yr is higher than in the Vera basin. Nevertheless, the Neogene marls, limestones and sandstones contribute to edaphic aridity. According to archaeological data, human settlement and land-use are recorded in the Vera and Penedes basins since the Neolithic period.

4 RESULTS

A Holocene chronosequence of 4 and 5 river terraces was established for the Antas (terraces H1, H2, H3a and H3b) and Aguas valleys (terrace H1, H2, H3, H4a, H4b), respectively. Unlike the late Pleistocene stage 2 deposits, the Holocene terraces are composed of well-stratified point bar deposits and form row terrace textures (Schulte, 2002b).

The oldest Holocene terraces H1 of the Aguas and Antas river date from the Atlantic Period. In the Aguas valley Chalcolithic sites (5000 – 4200 yr cal B.P.) were found on the H1 terrace surface. Radiocarbon dating on microcarbon, yields an age of 1040 ± 40 yr B.P. for the channel deposits of terrace H2. From the +2 m Holocene terrace of the Rambla Ancha, French & Passmore (1998) obtained a radiocarbon age of 1340 ± 50 yr B.P. During the Little Ice Age, the H3 terrace of the Aguas river and the H2 terrace of the Antas river were deposited. The H3, dated 430 ± 50 yr B.P. by radiocarbon, belongs to the beginning of the Little Ice Age (Figures 1 and 2). The youngest fluvial terraces of the two river systems (H4a and H4b in the Aguas catchment, H3a and H3b of the Antas river) were deposited during the 20th century as recent artifacts indicate. ^{210}Pb dating and artifacts point to a relatively high accumulation rate of flood deposits (1902 ± 4 A.D. at 85 cm depth) in the lower Aguas valley. Between the 1930's and the 1950's, the sedimentation rate amounts to 2.9 cm/yr compared to an average of 0.89 cm/yr between 1902 and 1998. These flood events correlate with the years with maximum annual precipitation of the 20th c. (1946, 1948, 1949, 1951 A.D.) recorded by the 128 year-precipitation series of Murcia, 80 km

northwest of the study area. Precipitation data prior to 1953 from the Vera basin are not available.

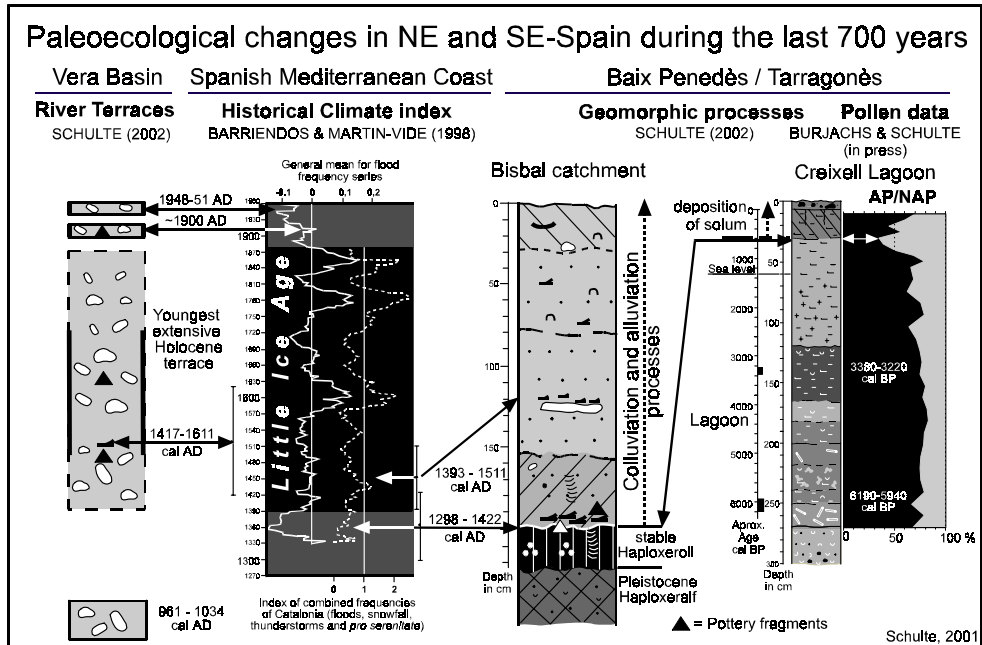


Figure 1. Synoptical paleoecological and morphological changes in the Vera and Penedes basins during the Little Ice Age. Chronology in calendar ages.

The lack of important tectonic uplift in the Penedes basin led to the erosion of low angle pediments at the basin margins and to the accumulation of Pleistocene fluvial terraces in the middle reaches, whereas flood plains formed near the coastline. The mapping of Holocene fluvial terraces under this specific morphological configuration is difficult. Therefore, pedological and sedimentological studies focused on several sections of Holocene floodplain deposits. The excellent exposures, which in some locations exceed 100 m width and the clear correlation between the profiles, make the synoptical stratigraphy shown in Figure 1 possible. The Pleistocene-Holocene boundary separates the early-middle Holocene Haploxerolls (organic soils) from the underlying late Pleistocene Haploxeralfs (reddish Mediterranean soils). Absolute dating of this youngest Haploxeralf was not possible. Its chronostratigraphy is based on the correlation with radiometric dated late Quaternary soil chronosequences of the Mediterranean Iberian coast (Schulte & Julià, 2001). In contrast, the Haploxerolls were formed predominantly during the more humid climate conditions at the beginning of the Holocene, shown by several pollen records (Burjachs *et al.*, 1997). Iberian, Phoenician and Roman pottery fragments in the upper part of the Haploxerolls (Figure 1) indicate land-use during historical time. However, a radiocarbon age of 585 ± 50 yr B.P. of *in situ* charcoals extracted from the top of the fossil Haploxeroll shows that its surfaces were relatively stable until the 14th century (Schulte, 2002c). After 585 ± 50 yr B.P. the soil was covered by colluvial and alluvial sediments. The fast accumulation (0.85 cm/yr), particularly during the 15th c. can be related to maximum clearance of woodland that has been shown by pollen records from a nearby coastal lagoon (Figure 1; Burjachs & Schulte, in press).

According to the obtained ^{14}C -datings (5300 ± 40 yr B.P. at 255 cm depth and 3090 ± 40 yr B.P. at 135 cm depth), the formation and subsequent paludal sedimentation of the lagoon commenced at the end of the Versilian transgression. At the beginning of the 15th c., the sedimentation pattern switched from the paludal deposition to an accumulation of reddish *solum* as a consequence of soil erosion on the surrounding hill slopes.

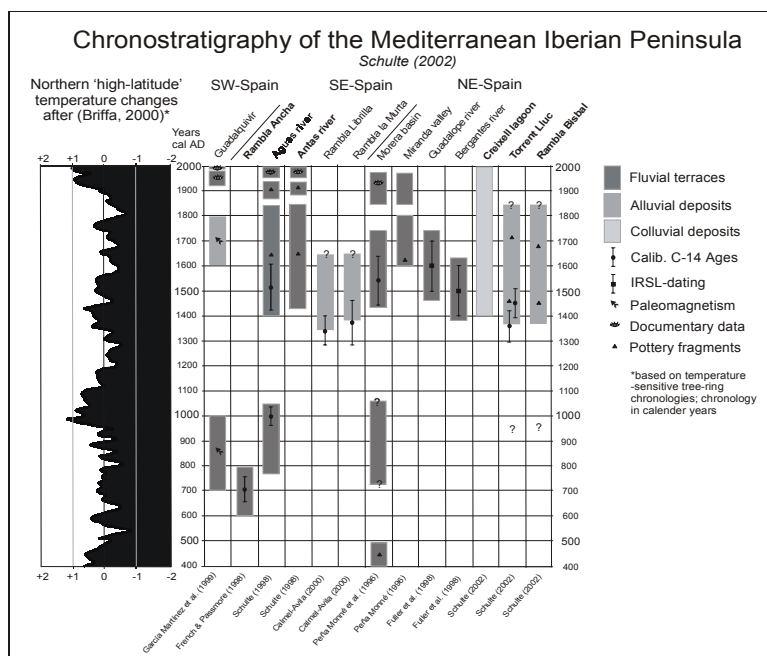


Figure 2. A 1600-year stratigraphy of fluvial terraces, alluvial and colluvial deposits of the Mediterranean Iberian peninsula.

5 DISCUSSION

The morphological, sedimentologic and pedological studies of the valley bottoms of the Vera and Penedes basins show important changes regarding the Holocene fluvial environments. The river terraces, alluvial and colluvial deposits result from different periods of fluvial erosion and accumulation. The origin of the fluvial terrace H1 in the Vera basin is climatically induced, although the Versilian transgression may have played an important role. Soil and travertine formation ($9,300 \pm 70$ yr B.P.; U/Th) can be ascribed to more humid climate conditions during the early Holocene (Schulte & Julià, 2001). Historical terrace deposition in the Vera basin occurred during the early Middle Ages, the Little Ice Age and in the 20th century. The erosion of a terrace generation and the accumulation of the next unit represent important morphodynamic changes, particularly an increase in flood magnitude and frequency. The deposition of the point bar deposits point to a meandering river system. Periods of sparse or moderate floods are characterised by stability or minor migration of the main channels.

The installation of the early Middle Ages terraces might be attributed to climatic factors. It can be concluded from the archaeological and historical data that this terrace formation was not caused by human impact. During the late Visigothic and early Arabian Periods, population density was low and agriculture was based on subsistence production. Pollen profiles from the Almería and Alicante Provinces indicate a maximum aridity at the beginning of the Middle Ages (*Burjachs et al.*, 1997). In contrast, human interference in the landscape related to land-use changes during the Christian conquest and the expulsion of the Muslims of the 16th c. may have played a certain role in river dynamics (terraces H3 in the Aguas, terrace H2 in the Antas river). The correlation between the river terrace accumulation in the Vera basin and the flood frequency series of the Spanish Mediterranean coast (*Barriendos & Martín-Vide*, 1998), illustrated in Figure 1, indicates that the accumulation of the terrace unit started at the beginning of the Little Ice Age and not during the major peaks of flood frequency around 1600, 1780 and 1850 A.D. However, the youngest small-size terraces of the 20th c. can be correlated with the secondary peaks around 1900 AD and the end of the 40's (Figure 1).

In the small-size catchments studied in Northeast Spain, human impact has led to increased surface run-off causing drastic alluviation and colluviation in the valley bottoms since the end of the 14th c., particularly during periods of maximum woodland clearance of the 15th c. Iberian, Phoenician and Roman pottery fragments in the upper part of the organic soil also demonstrate land-use during historical time, although no alluvial or colluvial deposits related to these periods were found. During the Roman Period intensive land-use (viniculture, olive groves, and wheat) were restricted to the lowlands of the Penedes basin. In contrast, the modern age woodland clearance affected the slopes of the surrounding mountains and led probably in this way to increased surface runoff and soil erosion. Similar to the findings of the Vera basin, the morphological processes correlate with the beginning of the Little Ice Age (Figure 1).

To find out the influence of climate or human control on fluvial processes in both study areas it is necessary to establish correlations with other Mediterranean rivers. Figure 2 shows a 1600-year stratigraphy of 13 fluvial catchments of Southwest, Southeast and Northeast Spain, studied by this research and by various authors (*García Martínez et al.*, 1999; *French & Passmore*, 1998; *Calmel-Avila*, 2000; *Peña Monné et al.*, 1996; *Fuller et al.*, 1998; *French & Passmore*, 1998). According to the stratigraphy, fluvial terraces were accumulated in some catchments during the Early Medieval Ice Advance (6th - 10th century), whereas fluvial activity during the Medieval Optimum was insignificant. However, in nearly all river systems sedimentation of fluvial deposits occurred during the Little Ice Age. The aggradation processes mostly started at the onset of this global climate period. The increased flood-events can be related to the southward shift of the Northern Hemisphere westerlies during the Little Ice Age.

6 CONCLUSIONS

Despite the different physiographic frameworks and sedimentation patterns, the reconstruction of river environments and associated erosion-accumulation processes of the southeastern and northeastern Iberian study areas shows a certain synchronism of fluvial dynamics. The 1600 year stratigraphy of 13 fluvial systems of Southwest, Southeast and Northeast Spain provides evidence for increased fluvial activity, during periods of cooler Holocene climate such as the Early Medieval Ice Advance and the Little Ice Age (*Schulte*, 2002a, 2002b). Cycles of river activity are interpreted as periods characterised by increased flood magnitude and frequency. From the available data it can be concluded that the human

impact on river dynamics in the Vera and Penedes basins may have been decisive in terms of magnitude of surface runoff and sedimentation yield, but is less important in triggering long-term Holocene river dynamics.

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11. THE RATE OF SEDIMENTATION ON REGULATED RIVER FLOODPLAINS: THE UPPER VISTULA AND THE UPPER Odra RIVERS, SOUTHERN POLAND.

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ABSTRACT

The upper Odra and the upper Vistula Rivers used to be naturally meandering rivers. The embankment constructions confined the river floodplain and changed the natural pattern of alluvial sedimentation. Regulation works arrested the lateral migration of the Vistula River. The Odra River course has been straightened. Differences in sedimentation in such different environments are noticeable. The flood sediments create the vertically accreted alluvia. The three different indicators were used to define sediment age. Due to 200 years of hard coal mining the finds of coal dust in the lowest parts of the profiles indicates that the surveyed sequence was deposited during the last 200 years. Upper parts of the alluvia also contain plastic objects (artefacts) and ^{137}Cs which were used to provide age estimates. Their presence proves that the deposits are relatively young and the rate of sedimentation seems to be rapid.

1 INTRODUCTION

Vertical accretion of sediments is one of the dominant process of floodplain formation (Leopold & Wollman, 1957). The majority of vertical accretion sediments results from the overbank deposition of suspended sediments load during floods. This has been shown to be the dominant process along many low gradient valley floors that show limited lateral accretion caused by widely shifting meander bends. Similarly, vertical accretion is also favoured where channel migration is inhibited by river engineering. In general, vertical accretion deposits are fine-grained and horizontally and sub-horizontally bedded layers. Each fining-up sequence is believed to represent a single flood event (Klimek, 1974). In these layers the coarse component of individual beds is deposited during early flood stages and the finer grained, less dense, component deposited during waning flood stages (Zwolinski, 1992).

Texture and thickness variability of vertical accreted sediments in different floodplain environments and time scales has received considerable attention (Macklin, 1985; Magillan, 1985; Zwolinski, 1992; Moody *et al.*, 1999; Moody & Troutman, 2000; Page *et al.*, 2001).

This paper focuses on vertical accretion sediment deposited during the last 250 years in the upper reaches of the rivers Odra and Vistula (Southern Poland). However since the beginning of the industrial revolution the composition of vertical accreted sediments has been altered by the introduction of new physical and chemical pollutants like coal dust,

heavy metals, synthetics (artefacts) and radionuclides (including ^{137}Cs) (Macklin & Klimek, 1992; Walling & He, 1997).

In this study rates of vertical accretion of floodplain sediments were determined utilising chronological markers provided by the first occurrence of coal dust, plastic artefacts and ^{137}Cs .

2 STUDY AREA

The rivers Odra and Vistula are meandering sand-bed rivers with average discharges of $41 \text{ m}^3\text{s}^{-1}$ and $62 \text{ m}^3\text{s}^{-1}$ respectively. Both of the investigated river reaches are located within submountainous basins of southern Poland: the Odra River in the Raciborz Basin and the Vistula River in the Oswiecim Basin (Figure 1). The areal extent of the catchment up to the investigated area averages 4666 km^2 for the Odra and 5301 km^2 for the Vistula River. The valley floor slope reaches respectively 0.4 and 0.3 m/km and the sediment transportation 322000 t/year for the Odra and 312000 t/year for the Vistula.

Maximum discharges usually occur in July in association with summer rainfalls in mountainous headwater areas. The natural processes of erosion and sedimentation on both rivers were disturbed in the 19th century when the authorities started the river regulation program for navigation purposes. Lateral migration and meander development of the Vistula River ended in 1926 because of stabilisation work (Czaja *et al.*, 1993). In the year 2000 a canal was constructed to bypass a series of prevented meanders (Figure 1).

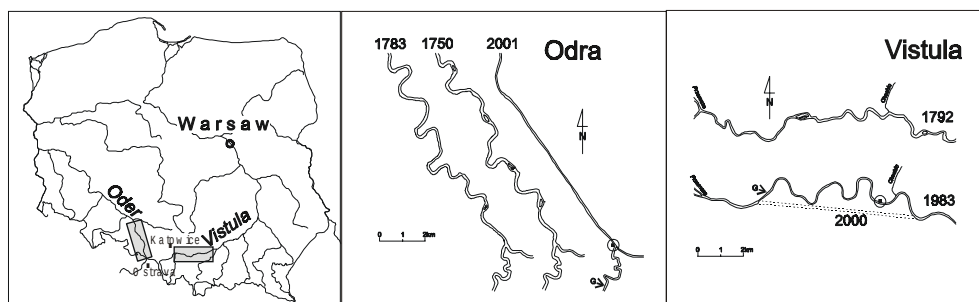


Figure 1. The Odra and Vistula Rivers are two the biggest rivers in Poland. Due to the regulation works the Odra channel has been straightened and the Vistula river banks have been stabilised. The gauging stations are marked with G and the study sites with black squares.

The upper course of the Odra River has been straightened (Figure 1). For the period 1940-2000 the average annual minimum water stage was about 130 cm and the average annual maximum stage was about 400 cm. Bankfull stage, which is reached at 470 cm, was exceeded 24 times giving way to floodplain inundation. The decline in the trend of the minimum water stage between 1940 and 2000 is consistent with minor incision of the riverbed.

Before regulation the Vistula was a mixed-load meandering river. River engineering works undertaken at the beginning of 20th century did not significantly change the river course (Figure 1). However, the banks were strengthened to prevent further lateral channel migration. The canal, which shortens a series of meander bends, was opened in 2000. For

the period of 1935-2000 the average annual minimum water stage was about 80 cm and the average maximum water stage was about 460 cm. Bankfull stage is at approximately 400 cm. This stage was exceeded 44 times in the period of record.

The Upper Odra River and Vistula land use is characterised by agriculture and some industrial centres. The valleys itself are used for agricultural purposes. Hard coal mining started in the middle of 18th century in Katowice in 1750 AD and in Ostrava in 1763 AD. Hence these dates provides the maximum age for coal dust supply to the tributaries.

3 METHODS

Floodplain sediments were examined at sites on the Odra and on the Vistula River (Figure 1). Pits were excavated adjacent to the channel up to the groundwater level (approximately 3 m below surface). Sediment samples were collected from every layer. Grain size distribution was determined by sieving at 0.25 phi intervals. The presence of ¹³⁷Cs was determined for the grain size finer than 0.4 phi in gamma ray spectrometer. The coal dust layers and artefacts were found by direct visual inspection in the field.

To define the flow regime at each site annual data for maximum and minimum water stage were collected for river gauges at Chalupki for Odra and Gromiec for Vistula (Figure 1.). Sequences of channel change for both rivers the Odra (1750 and 1783) and the Vistula (1792) were determined from historical maps.

4 RESULTS

4.1 Odra site

The vertical section on the Odra riverbank extended from the surface to a depth of 320 cm (Figure 2). The deposits consist predominantly of layers of sand and silty sand. The low part consists of massive gravely sand deposited as the channel facies. The deposits in the middle part show of alternating layers of silty sand and sandy silt. The material in the lower and middle parts of the profile was deposited in the period before the regulation work. Then the site was located at some distance from the channel. The massive silty sand in the top of the profile contains ¹³⁷Cs and represent the youngest deposits.

Riverbed massive gravel is shown in the lower part of the profile. As grain size depends on the flood event magnitude, very thin layers in the middle part of the profile result from relatively lower flow regimes given prior to river regulation. The total thickness of the post-regulation accretion sediments is approximately 90 cm. Due to the relatively high river incision only the finest material is able to be deposited at present.

The first layer containing coal dust occurs at the depth of 260 cm. The ¹³⁷Cs which first appeared in the atmosphere in the early 1950s, occurs in the upper 83 cm of the profile. The sediments containing coal dust but lacking of ¹³⁷Cs are assumed to have been deposited between 1763 and 1950 with an average vertical accretion rate of 0.9 cm/year. The vertical accretion rate since 1950 increased to approximately 1.7 cm/year (Figure 3).

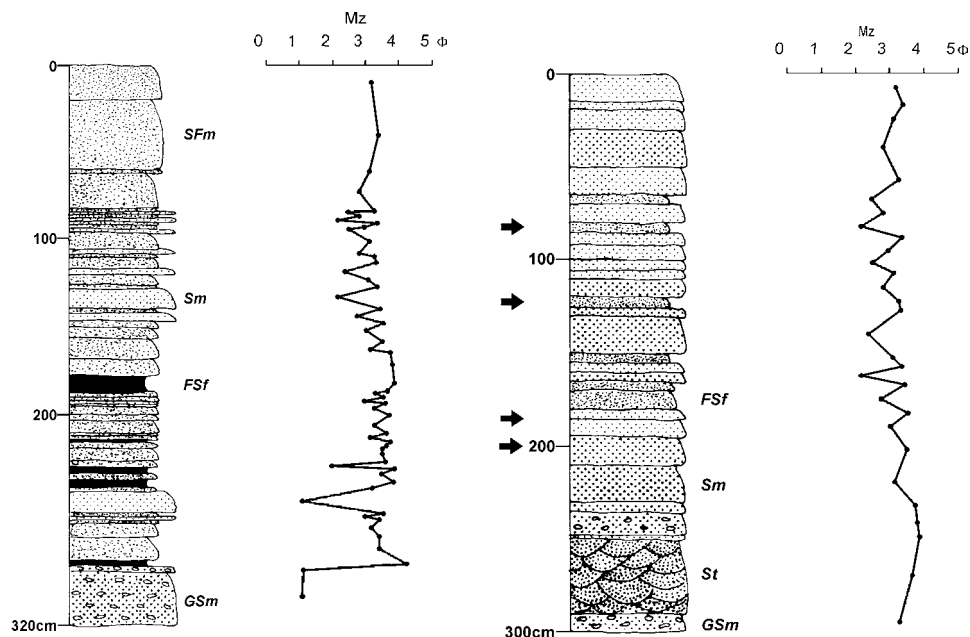


Figure 2. Sedimentary logs of the profiles of the Odra (left) and the Vistula (right) sampled sections. The Odra deposits consist mainly of very thin layers of silty sands and thicker layers of fine sand. The medium grain size fines up in the profile due to the increasing banks height and not to the channel lateral migration as it occurs at the naturally meandering rivers. The Vistula deposits consist mainly of sand. The massive gravely sand and the cross-stratified sand in the base of this profile prove that previously the sediments were deposited at the point bar. The Mz for this profile oscillates between 1.5 in the middle part and 3 phi in the upper part. The arrows mark the layers with artefacts found in the profile. Key to facies code by Zielinski (1988)

4.2 Vistula site

The Vistula River bank exposure reveals a sequence of vertical accretion sediments. This alluvium is deposited in a point bar position, adjacent to older sediments of a scrolled floodplain created by lateral migration in the period before the regulation works were undertaken. The deposits at the base of the profile are poorly sorted and dominated by mixed massive gravel and cross-bedded coarse sand (Figure 2.) The upper 210 cm of the profile are dominated by alternating layers of sand and silty fine sand. The structure of these layers deposited at the arrested point bar is similar to the deposits of levees. Similarly to the Odra profile the grain size is generally finer in the upper part. Usually the grain size tends to fine up the profile. The grain size distribution at the Vistula site is the finer in the middle part of the profile because of a large flood in 1997, which formed a thick layer of coarse-grained deposits at the top of the sequence

The coal dust appears in the profile at the depth of less than 250 cm. Plastic artefacts from younger than 1950 appear at a depth of 200 cm (Figure 3.). Given that the first coal mine within the upper Vistula catchment commenced extraction in the year 1750 the rate of vertical accretion between 1750 and 1950 is approximately 0.25 cm/y.

Since 1950 the rate of vertical accretion has increased sharply to an average of 4 cm/y. However, an object found at a depth of 120 cm is thought to have been produced in

approximately 1985. This gives a minimum vertical accretion rate of 8 cm/year during the last 15 years (Figure 3).

5 CONCLUSIONS

The investigated floodplain deposits of the Vistula and Odra Rivers, deposited in the zone adjacent to the river channel, are dominated by vertically accreted sets of sand and silty sand bed represent a significant flood event. The river engineering works described in this paper terminated the channel migration. The pre-existing Odra channel was straightened and that of the Vistula was fixed. The engineering works appear to have resulted in some riverbed incision. The absence of lateral channel migration has ensured that the study sites have maintained their proximity to the channel position since the regulation. Although each layer is supposed to represent a single flood event, it is not possible to exclude the intervening erosion. Moreover not every flood is represented in the profile. Three different age indicators were used to calculate rates of vertical accretion since approximately 1750: coal dust, plastic artefacts and ^{137}Cs . The coal dust can be used to estimate rates of sedimentation on the Vistula and Odra Rivers between 1750 and 1950. Due to the absence of artefacts in Odra site the subsequent accretion rates were here provided by the presence in sediments of ^{137}Cs . Synthetic artefacts were present in the Vistula River site. Both sites provide evidence of increasing rates of vertical accretion during the last 50 years. The very high recent sedimentation rate on the Vistula floodplain (8 cm/year) in part reflects heavy deposition during the large flood of 1997 when deposits up to 30 cm thick were formed on the floodplain. The rate of sedimentation in this period is much more significant for the Odra River (1.68 cm/year).

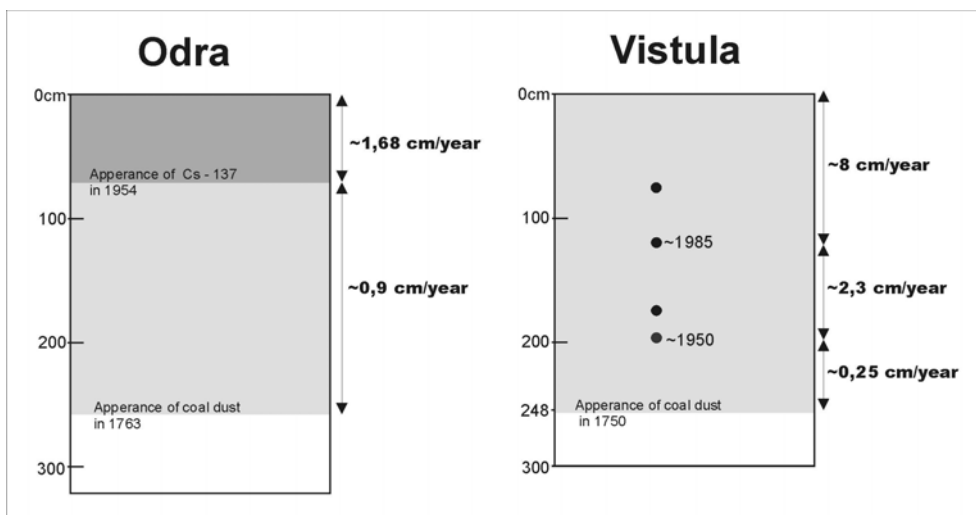


Figure 3. The rate of the overbank sedimentation in both sites. The dots in Vistula profile mark the artefacts occurrence. In the Odra profile where the artefacts don not occur the ^{137}Cs was used to determine the age of the youngest sediments. High rate of recent sedimentation is caused by heavy flood in 1997 which has left up to 30 cm of deposits near to the channel edge.

The increasing rates of vertical accretion since 1950 can be associated with the increasing frequency of floods. The increasing sedimentation on the Vistula River is due to the increased frequency of floodplain inundation. Similarly the average flood stage has increased in the Odra River. The average flood stage on Vistula River was 142 cm and for Odra 74 cm. The more often and more intensive flood events cause the overbank sedimentation. Also the river planform is important for sedimentation rate. The meandering channels (Vistula) favour sedimentation processes more than the straight channel (Odra) where the transportation is the dominating process.

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12. CLUSTERING OF FLOOD EVENTS IN THE CONTEXT OF INCREASED HUMAN ACTIVITY

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ABSTRACT

The frequency of large floods fluctuates in various climatic regions as well as in time. The specific feature of clustering of floods is lack of time for relaxation and therefore it follows the rejuvenation of the system or its earlier maturing. The author describes examples of flood clusters in present-day and historical records turning special attention to acceleration of processes connected with human activity.

1 INTRODUCTION

Depending on the climatic regime the recurrence interval of large floods may fluctuate from 10^2 - 10^3 years in extreme arid regions to several decades and even to several years in temperate zones, the mediterranean and in the humid tropics. However in extremely humid areas the passing of bankfull discharge may be repeated every year or even several times in one year. The same happens in cold climate regions with permafrost where regular snow-melt floods occur.

The frequency of large floods fluctuates in time. The clusterings of extreme rainfalls and floods may appear in various climatic zones. The specific feature of a cluster is a short time interval between consecutive floods with no or very short time for relaxation. The channel-floodplain system transformed by one flood, cannot return to the previous shape and size, because the next event follows (*cf. Burkham 1972*). The river banks and channel bars can not be stabilised and revegetated (*Starkel, 2002*) and clustering of several floods can promote either channel incision or aggradation.

Several types of flood clusters that have variable duration and recurrence intervals can be identified. These are:

- a) clusterings of floods usually with 2-3 yrs recurrence interval, separated by 1-2 years without larger floods.
- b) floods repeating during every consecutive year (usually 2-3 yrs long)
- c) clusters of several floods during one year or one rainy season when consecutive floods reinforce geomorphic change. Among them may be floods of various origin (rain and snow-melt). Several peaks can appear even during one flood period, when consecutive heavy downpours are superimposed on the continuous rain (*Starkel et al. 1998*).

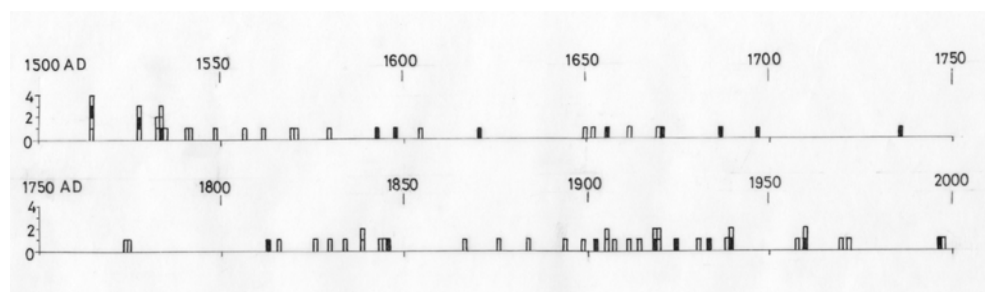


Figure 1. Extreme floods and other large floods of the Vistula river recorded in Cracow from AD 1500 (based on written sources, flood marks and hydrological records, based on data collected by Bielański 1984). Black blocks represent extreme floods.

2 EXAMPLES OF CLUSTERINGS IN PRESENT-DAY AND HISTORICAL RECORDS

The clustering of heavy rains and floods have been recognised in Europe (Figures 1 and 2) and in other parts of the world (Benito *et al.* 1996, Brazdil *et al.* 1999, Starkel 2001). In the upper Vistula valley during the last two centuries there were recorded 32 years with large floods including a cluster of 3 large floods in 1843-45 and 4 floods in 1919-1920 (after Bielański 1984). In the 16th century 23 floods were noted during 15 years with three clusters: 4 and 3 floods in (1515 and 1528) respectively and 6 floods in 1533-35 (Figure 1). A distinct change in river channels by aggradation and widening was recorded in three years, 1958-60, in the Western Carpathians (Ziętara 1968), while at the same time the channel of Dunajec river had been deeply incised (Froehlich 1975). Similar deepening of the Ropa channel in bedrock by 0.5 m took place during clustering of floods in 1970-74 (Soja 1977). During continuous rains in July 1997 at the eastern margin of affected areas there followed heavy downpours, which caused a sequence of flood waves (Froehlich 1998). As the effect of that channel width was extended two times and more at some transects. The role of the clustering of floods over centennial time scales has been well recognised in the case of the Gila river channel in Arizona, which later returned to its previous narrow shape (Burkham 1972).

In Spanish river valleys floods of various sizes were recorded during the last millenium (Benito *et al.* 1996). In the case of the Ebro valley the decades 1770-1780 (6 large floods and 10 others) and 1860-1900 (4-6 large floods and 15-35 others in one decade) were particularly rich in floods. In Northern England Rumsby and Macklin (1996) connected phases of channel incision and the start of the formation of new alluvial fills, with the clusterings of large and moderate floods in the periods 1760-1800, after 1875 and in the 1950-s.

In the upper River Rhine Naef (2002) calculated the mean number of floods, which passed 0,4 events per year (4 per decade) between 1755 and 1780 and 1840-1845. Flood clusters were especially common during the Little Ice Age (Brazdil *et al.* 1999, Starkel 2001).

For the monsoonal climate of India, Kale (1998) has mentioned similar clustering of floods in various river valleys. Even for the largest rivers like the Brahmaputra there are several characteristic flood waves during one summer monsoon, transforming the pattern of bars in the braided channels, shifting them up to several hundreds of meters. The impact of

such clustering on channel widening and aggradation has been recently described by *Starkel* and *Sarkar* (2002) from the foreland of the Bhutanese Himalaya (caused by flooding in 1993, 1996 and 1998).

3 EXAMPLES OF CLUSTERING IN HOLOCENE RECORDS

It is not easy to prove the presence of flood clusterings in sequences of alluvial sediments. In the rocky canyons of the southwest USA the analysis of slack-water deposits deliver the exact information about the presence of consecutive events (*Enzel et al.* 1996). The rises of the Dead Sea by several tens of meters may be explained only by a series of heavy floods (cf. *Frumkin et al.* 1991).

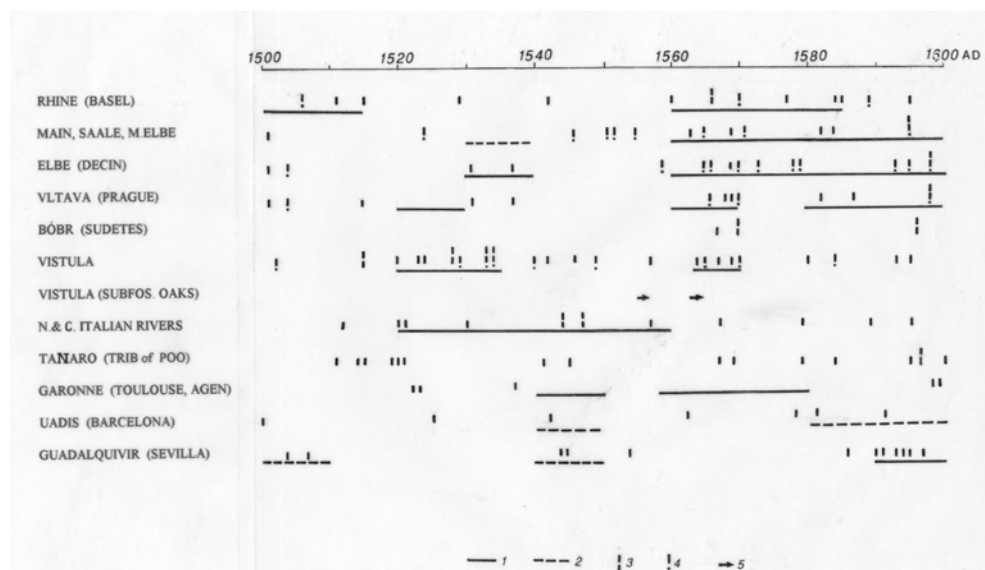


Figure 2. Floods in selected Central-European river valleys in 16-th century based on records published by *Brazdil et al.* (1999), supplemented by records from Polish rivers (after *Starkel* 2001). Key: 1) main phases of frequent floods, 2) less distinct phases, 3) floods in single years, 4) snowmelt floods, 5) subfossil oaks found in alluvia.

About one hundred floods registered during a humid phase 8.4-7.8 kyr BP in the small alluvial fan in Podgrodzie at the Carpathian margin is grouped in the clusters of layers (5-10 each), separated by breaks, represented by peaty or buried soil horizons (*Starkel et al.* 1996). Flood clusterings may be reconstructed from buried subfossil oak trunks, found in Southern Germany (*Lauschner et al.* 2000) and in S. Poland (*Krapiec*, 2001). The presence of several trunks from the same decade at various localities (gravel pits) in the upper Vistula valley can be interpreted as the clustering of floods, similar to clusters known from the 16th or 19th century AD. There is a case with oak trunks deposited between AD 465 and 480 and AD 1025-1040 (*Krapiec* 2001).

4 EFFECTS OF FLOOD CLUSTERS IN THE ENVIRONMENT TRANSFORMED BY HUMAN ACTIVITY

In forested areas under natural vegetation the clustering of floods is usually reflected in the downcutting of river channels in their upper reaches and in the lateral migration or aggradation in the lower reaches. In river catchments transformed by deforestation, soil cultivation, overgrazing and direct intervention in the drainage pattern, the rates of geomorphic processes and sediment transfer are much higher. Therefore the change in the channel shape and size during the clustering of flood events may be so great, that the relaxation and return to the previous conditions cannot occur and the aggradation in various valley reaches of the longitudinal profile is shifted either upstream and/or downstream. In the degraded geoecosystems of steep-land catchments not only does the total suspended and bedload increase, but during the progressing clusterings so does the frequency of moderate floods. This explains the appearance of several floods waves during one rainy season observed in the smaller catchments of Lish, Gish or Mahananda rivers at the margin of the Darjeeling Himalaya (Dutt 1966, Starkel *et al.* 1998).

High sediment load results in the aggradation in various parts of the longitudinal profile, including upper reaches, affected by debris flows. This is well observed at the junctions of mountain streams in the Alps and Carpathians (cf. after floods in 1958-60, Ziętara 1968).

In the case of the Himalayan margin, despite tectonic uplift, aggradation also proceeds upstream. High rates of upbuilding of alluvial fans (reaching 1-3 m in one decade) is not only connected with heavy bedload, but also with the infiltration of water in the permeable substratum, followed by rapid reduction of stream discharges. Therefore, in the marginal area of the Bhutanese Himalaya, where clusterings of large floods were recently observed and the deforestation and cultivation are less widespread (in comparison to Darjeeling Himalaya) we register even quicker extension of braided channels (Starkel and Sarkar 2002).

In the acceleration of runoff a leading role is played by dense road patterns, which provoke the clustering of floods. In deforested areas these roads initiate badlands development and debris flows, but in the forested areas the dense road pattern only accelerates the deepening of river channels and cart-roads.

A negative role is played by the regulation and embankment of river channels. In the case of the Vistula river catchment, the channels in the Subcarpathian Basins were regulated and then the outflow increased. Downstream the river has not been regulated, remained braided and especially during clusterings of flood, aggradation is continuing. The section upstream works like a flume and downstream deposition follows. Similar sequences have been observed in many smaller valleys of the Vistula catchment, where downstream of recently regulated sections the populated valley floor cut by a shallow meandering channel started to be inundated every year, even several times both during snowmelt periods and after heavy downpours.

The construction of embankments close to the river channel (this is the case in most European river valleys) causes rapid deposition within embankments during frequent floods (clusterings) that there is no time to raise them and later on follows the breaking of ramparts and catastrophic flooding of former natural floodplain (Gebica and Sokołowski 2000). Frequently after that the avulsion of the river channel may follow, especially when flood clustering continues.

5 LONG-TERM GEOMORPHIC ROLE OF FLOOD CLUSTERING

The clustering of floods is a common feature of hydrological regimes. The examples described show the role of clustering in the evolution of fluvial systems (cf. Starkel 1998, 2002). Lack of time for relaxation and revegetation during the clustering of floods may change the character of river channels or result in avulsion followed by channel incision or aggradation. In the case of high bedload within middle and lower courses a tendency to braiding and aggradation of the river bed, occurs, whereas in reaches with high suspended load floodplain accretion and a tendency to avulsion is more frequent. The opposite trend to downcutting is not only restricted to headwaters but also is common in regulated straightened rivers and in the reaches where there is extraction of gravel and sand. It may be concluded that the reaction of different river catchments and river channels to the clustering of floods may be different. In every case a short recurrence interval of large floods accelerates rates of erosion and deposition. Therefore, knowledge of mechanism and effects of flood clustering both in the natural and human altered environment is very important for effective water management and land use. This is especially true during periods of global climatic change manifested by a rise in the frequency of extreme events.

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