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Review paper

Human impact on fluvial regimes and sediment flux during the Holocene: Review and future research agenda

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ABSTRACT

There is a long history of human–riverine interactions throughout the period of agriculture that in some regions of the world started several thousand years ago. These interactions have altered rivers to human dominated systems with often negative impacts on fluvial environments. To achieve a good ecological and chemical status of rivers, as intended in the European Water Framework Directive (WFD), a better understanding of the natural status of rivers and an improved quantification of human–riverine interactions is necessary. Over the last decade the PAGES-LUCIFS (Land Use and Climate Impact on Fluvial Systems) program has been investigating both contemporary and long-term (centuries to millennia) river responses to global change with the principal aims of: 1) quantifying land use and climate change impacts of river-borne fluxes of water, sediment, C, N and P; 2) identification of key controls on these fluxes at the catchment scale; and 3) identification of the feedback on both human society and biogeochemical cycles of long-term changes in the fluxes of these materials. Here, we review recent progress on identifying fluvial system baselines and quantifying the response of long-term sediment budgets, biogeochemical fluxes and flood magnitude and frequency to Holocene global change. Based on this review, we outline the future LUCIFS research agenda within the scope of the PAGES-PHAROS (Past Human-Climate-Ecological Interactions) research program. Key research strategies should be focused on: 1) synthesising the data available from existing case studies; 2) targeting research in data-poor regions; 3) integrating sediment, C, N and P fluxes; 4) quantifying the relative roles of allogenic and autogenic forcing on fluvial regimes, extreme events and sediment fluxes; 5) improving long-term river basin modelling; and 6) integration of LUCIFS with other research communities within PHAROS, namely HITE (land cover) and LIMPACS (water quality and biodiversity).

Contents

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1. Introduction

Evidence from alluvial archaeology indicates a long history of human–riverine interactions throughout the Holocene (Brown, 1997) with six chronological phases of river use (Table 1) identified by Downs and Gregory (2004). Whilst society has, in general, benefitted from the natural resources afforded by rivers and floodplains, over recent decades it has become apparent that river management has, on balance, led to negative impacts on fluvial environments including reduced floodplain biodiversity and modified flow regimes (Phases 1 to 5 in Table 1). Human occupation (housing and economic activity) of floodplains has also increased, reflected in the rising economic losses from flood disasters. Between 2000 and 2004, 63 floods in the EU15 countries accounted for $25.4 billion damages, with over half a million people affected (Lamothe et al., 2005). This is unlikely to reduce in the short to medium term due to the lack of effective planning or legislation aimed at preventing or reducing development on floodplains within Europe. It is within this context that sustainable river basin management (Phase 6, Table 1) has emerged as a new paradigm supported by environmental legislation in developed regions and research programs globally (e.g. river basin twinning projects of the EC Framework Programmes). In Europe the 2001 Water Framework Directive (WFD) was introduced to improve the quality of freshwater ecosystems, including rivers. More recently the 2007 Directive on the Assessment and Management of Floods (DAMF) was formulated, the scope of which is to develop new flood risk management plans to reduce damage to human health, the environment, cultural heritage and economic activity (EC, 2007). Implicit within DAMF is the concept of giving rivers more space whilst also considering the maintenance and/or restoration of floodplains. Whilst observational data (e.g. from remote sensing) and information from the instrumental period are clearly important for understanding river system behaviour, the timescales (centuries to millennia) of historical river management in many regions imply that a longer-term perspective on fluvial system response is of relevance. For example, the lower River Rhine has witnessed flood management for over 1500 years meaning that to gain a comprehensive understanding of the resulting magnitude, direction and timescales of change, a historical perspective is required (Hudson et al., 2008). A long-term approach is equally relevant when looking at questions concerning the impact of climate change on flood magnitude and frequency (Ely et al., 1996) given that instrumental records are often of insufficient length to provide conclusive data (e.g. Robson, 2002). Linking an understanding of the geomorphological evolution of floodplains with palaeoecological data can provide valuable insights into the natural and semi-natural functionings of floodplain environments informing floodplain conservation and restoration efforts (Brown and Quine, 1999; Brown, 2003; Sear and Arnell, 2006; Walter and Merritts, 2008).

Over the last decade the PAGES-LUCIFS (Land Use and Climate Impact on Fluvial Systems) program has been investigating both contemporary and long-term river response to global change with the principal aims of: 1) quantifying land use and climate change impacts of river-borne fluxes of water, sediments, C, N and P; 2) identification of key controls on these fluxes at the catchment scale; and 3) identification of the feedback on both human society and biogeochemical cycles of long-term changes in the fluxes of these materials in different environmental settings (Fig. 1, Dikau et al., 2005; Houben et al., 2009; Walling and Webb, 1996; Wasson, 1996). The main aim of this paper is to highlight the benefits of taking a long-term approach (centuries to millennia) for understanding the magnitude, direction and timescales of change in fluvial systems to enable informed decisions for effective sustainable river management. In the first part of the paper we review recent progress in: a) identifying baselines and trajectories of change through time; b) quantifying sediment budgets and biogeochemical fluxes; c); elucidating flood response to climate change; and d) predicting river response to future global change. In the second section we focus on the future research agenda and identify key areas where new data or approaches are required including: a) the organisation and analysis of existing data; b) the application of new techniques; c) the need to develop new synergies with other research disciplines; and d) the application of exploratory and predictive modelling. The paper concludes with a program of research to address the main priorities raised. Further details on technical and methodological aspects of LUCIFS, particularly in relation to sediment budgets, are covered by Brown et al. (2009a).

2. Fluvial systems: the long-term perspective

Over the last 2.6 Ma the Milankovitch forced fluctuations in global climate have driven fluvial change at the millennial scale. Over the last 0.9 Ma global hydrology has responded to the dominant 100 ka climate cycle with the Holocene being a period of ice-sheet minima, high global temperatures, and high precipitation; with a marked

Table 1
Chronological phases of river management (modified from Downs and Gregory, 2004).

Chronological phase	Characteristic development	Management methods employed
1. Classical “hydraulic” civilizations	River flow regulation, irrigation, land reclamation, arable farming	Dam construction, river diversions, ditch building, land drainage, check dams, cisterns
2. Pre-industrial revolution	Flow regulation, fish weirs, drainage schemes, water mills, navigation	Land drainage, in-channel structures, river diversion, canal construction, dredging
3. Industrial revolution	Industrial mills, cooling water, power generation, water supply, irrigation	Dam construction, canal building, river diversion, channelization
4. Late 19th to mid 20th C.	River flow regulation, flood defence, multiple use projects	Large dam construction, river diversion, channelization, structural revetment, river basin planning
5. 1950 onwards	Flow regulation, integrated river use projects, flood control, conservation management	Large dam construction, river basin planning, structural and bioengineered revetments, mitigation and restoration techniques
6. Late 20th and Early 21st C.	Conservation, sustainable use river projects	Integrated river basin planning, flow re-regulation, mitigation and restoration

Environmental Transformation / Relief classes	Advanced industrial	Industrial Agricultural	Developing Industrial (a)	Developing Industrial (b)	Rapidly Industrializing	Agrarian	Pioneer Settlement
High Mountains	Swiss Alps	Southern Alps (NZ)	Caucasus			Himalayas	
Mountains		Murray-Darling		Java			Andes
Uplands		Great Plains (USA)	Stovrapol Highland (Russia)	Indus-Ganges Plain	Mexican Basin	Northern Thailand	Kalimantan
Lowlands	Sweden	Australian Wheat belt	Russian Plain	NE China	Western Java	Nigeria	Amazonian
Coastal Plains	NE USA	SE Canada	Baltic States	Eastern South Africa	Southern Thailand	Bangladesh	Sumatra

Fig. 1. Categories of the "Land use and climate impacts on fluvial systems during the period of agriculture" (LUCIFS)-program according to land use characteristics (i.e. extend of human impact) and a simple physigraphic index reflecting both climate and tectonics. Modes of environmental transformation are taken from Kates et al. (1993). Relief is classified according to Milliman and Syvitsky (1992) based on maximum altitudes: high mountains > 3000 m, mountains 1000–3000 m, uplands 500–1000 m, lowlands 100–500 m and coastal plains < 100 m.

interglacial pole to equator distribution of water availability (e.g. soil moisture and runoff). Added to this global pattern are regional to local effects of altitude, land–sea distribution and geologically inherited groundwater catchments. The picture is further complicated during the Holocene with increasing human activity, both through deliberate management and inadvertent impacts, that have affected both the hydrological cycle and sediment regimes (Hollis, 1979; Arnell, 2002). Ever since humans started to significantly alter the characteristics of the land–atmosphere interface there has been anthropogenic impact on the hydrological cycle. The key development for the Earth's hydrological system was agriculture, the start of which heralded not only a societal revolution but also instigated anthropogenic impact of river basins. Agriculture evolved on each inhabited continent at different times and under different conditions (Bellwood, 2005) but in the modern era has been incremental in both its extent and effects. Agriculture also facilitated industrialisation and urbanisation, which are the second great drivers of catchment modification. The hydrological effects are therefore complex, relating to changing natural boundary conditions and incremental human impact leaving most river basins with a strong inherited or historical component. A long-term perspective is therefore required to be able to identify meaningful change in our river systems, to understand what the driving forces of that change are and also to be able to test hypotheses which implicitly or explicitly include a hydrological component. For example it was recently argued by Ruddiman (2003) that high mortality rates due to the Black Death in Medieval Europe caused forest regeneration, a reduction in CO_2 levels in the atmosphere and that this triggered the Little Ice Age. Such a hypothesis can only be tested in a convincing manner by using long-term data. Was there large scale forest regeneration in Europe and did this affect catchment runoff?

The highly diachronous evolution of agriculture, industrialisation and urbanism implies highly diachronous changes in catchment conditions and hydrological management. Due to a combination of the natural resilience in catchments, variable connectivity and the highly localised nature of early agricultural practices it is hard to identify an initial starting point for these catchment transformations. For example, although the development of irrigation in the Tigris–Euphrates area as early as the 4th century BC probably had some local hydrological impacts the catchment hydrology was not significantly impacted. Indeed although it may appear somewhat circular probably the best indicator of widespread catchment scale modification is the transformation of downstream sedimentary conditions and particularly a change in the nature of alluviation and an increase in floodplain sediment deposition (Macklin and Needham, 1992; Brown, 1997; Xu, 1998; Knox, 2006; Hoffmann et al., 2009a; Brown et al., 2009b). If we use this as a crude chronological marker then we see the period of major transformation in Europe being from the Bronze Age onwards (c. 3 ka, e.g. Kalis et al., 2003), in China from a similar period (Dearing, 2008), and from the European colonisation in America (c. 0.5 ka, Walter and Merritts, 2008), Australia (Olley and Wasson, 2003) and much of Africa.

2.1. Identifying baselines and trajectories of change over time

The identification and assessment of changes in fluvial systems, both due to natural and anthropogenic forcing, require a baseline state description as a reference (Dearing et al., 2006). In particular our judgements on the state of human modified rivers demand that we are able to define or reconstruct the natural form and functioning of the river. Baselines not only allow us to determine to what extent a river has changed, e.g. due to human interference, but may also guide river managers to identify key sustainable strategies for restoring a river system to a more natural or ecologically sound future state. With the EU Water Framework Directive a legal framework has been established to protect and restore clean water across Europe and ensure its long-term, sustainable use (Sear and Arnell, 2006). To achieve the goal of a good ecological and chemical status for all of Europe's surface waters and groundwater by 2015, baselines are needed against which to test the present-day state of rivers, while appropriate targets must be determined for improvement. The "status" of rivers essentially comprises both the biotic and abiotic (sediment load and geochemistry) components of the river ecosystem. The former can be assessed through palaeoecological studies (e.g. Brayshay and Dinnin, 1999; Davis et al., 2007), the latter through sediment budget approaches (Hoffmann et al., 2007; Brown et al., 2009a; Notebaert et al., 2009) including the analysis of floodplain contamination with heavy metals (Middelkoop, 2000). In terms of the functioning of river systems it is also pertinent to consider the long-term trajectory of flood magnitude and frequency. Studies from catchments in the USA that were affected by major anthropogenic impact much later than in Europe suggest that both river management and sediment regimes had major impacts on flood magnitude and frequency relationships, primarily due to floodplain aggradation increasing bankfull discharges (Costa, 1975; Knox, 2006; Walter and Merritts, 2008). Indeed Walter and Merritts (2008) state that these changes would have been evident in Europe over longer timescales; this is implicit in the Stable Beds Aggrading Banks model of floodplain evolution developed by Brown et al. (1994) for low energy UK river systems.

Indeed the morphology and functioning of some river reaches have, however, been so modified by humans over such long periods of time so as to be indivisible from a natural state. Interestingly not all modifications are detrimental, for example, palaeoecological studies suggest that human modified floodplains can increase biodiversity (Brayshay and Dinnin, 1999). A good example is the creation of flood or hay meadows which now contain several floral and faunal rarities. Davis et al. (2007) used fossil beetles from several small rivers in southern England to show how Medieval floodplains had high biodiversity due to high patch heterogeneity under intermediate disturbance regimes. It may, therefore, be both impossible and undesirable to separate natural state components from inherited cultural components in fluvial systems and particularly in rivers with long histories of human intervention such as the Rhine (Hudson et al., 2008). Indeed the cultural elements may be protected under heritage legislation (e.g. Medieval bridges) and so be immovable constraints to river restoration. In such situations the answer may lie in identifying “fluvio-cultural units” units where there is a functioning combination of natural morphology and processes with historical floodplain features (Fig. 2). In Northern Europe these will frequently be multi-channel rivers with mills, weirs, flood embankments, sluices, aqueducts, fords, causeways and ponds. In many cases it is likely that the very existence of multiple watermills on alternating sides of the floodplain and with secondary leats and mill races is an adaptation of naturally multiple anastomosing river channels. In some parts of Europe, rivers were deliberately allowed and encouraged to flood and deposit nutrient-rich fine sediment over the floodplain — in what are called watermeadows in the UK and by what is known as the process of “warping” (Brown, 1997). These management practices are also highly pertinent to sediment budgets and the storage of contaminants in floodplains (see Section 2.2). An approach that could now be taken is to compare such fluvio-cultural reference states and base line conditions of floodplain contamination with the output of models in order to further our understanding of how cultural components have interacted with natural processes to produce the ecological and geochemical conditions we see today. The next sections will consider this in respect to sediment budgets, biogeochemical fluxes and flooding.

2.2. Sediment budgets

Long-term sediment budgets are an important tool for reconstructing the trajectories of sediment loads in rivers to help understand the links and discontinuities between sediment sources and sinks in geomorphic systems and to help elucidate fluvial response to land use and climate change (Lang et al., 2003b; Brown et al., 2009a). According to Reid and Dunne (1996) “a sediment budget is an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin”. Sediment budgets incorporate sediment production/erosion, transport and deposition throughout the river basin including hillslopes, alluvial fans, river channels and their corresponding floodplains (Fig. 3). At short time scales, the links between the different sediment budget components are estimated based on the instrumental measurement of sediment fluxes. Changes of sediment storage are then inferred from differences of fluxes between successive components. Over longer (centennial and millenial) time-scales, budgeting of sediments rely on the measurement of changing sediment volume between the different storage components. Wasson (1996) developed an organisational framework for reconstructing the history of sediment fluxes, based on a material budget that included all the major components of river catchments (Wasson, 1996):

$$T = \mathrm{SLe}–\mathrm{SLs} + \mathrm{Re} + \mathrm{Ge}–\mathrm{Gs} + \mathrm{Ce}–\mathrm{Cs} + \mathrm{RIVe}–\mathrm{RIVs},$$

where

$T =$ flux of sediment, P or C;
SLe, SLs = sheet erosion and deposition at hillslopes
Re = rill erosion

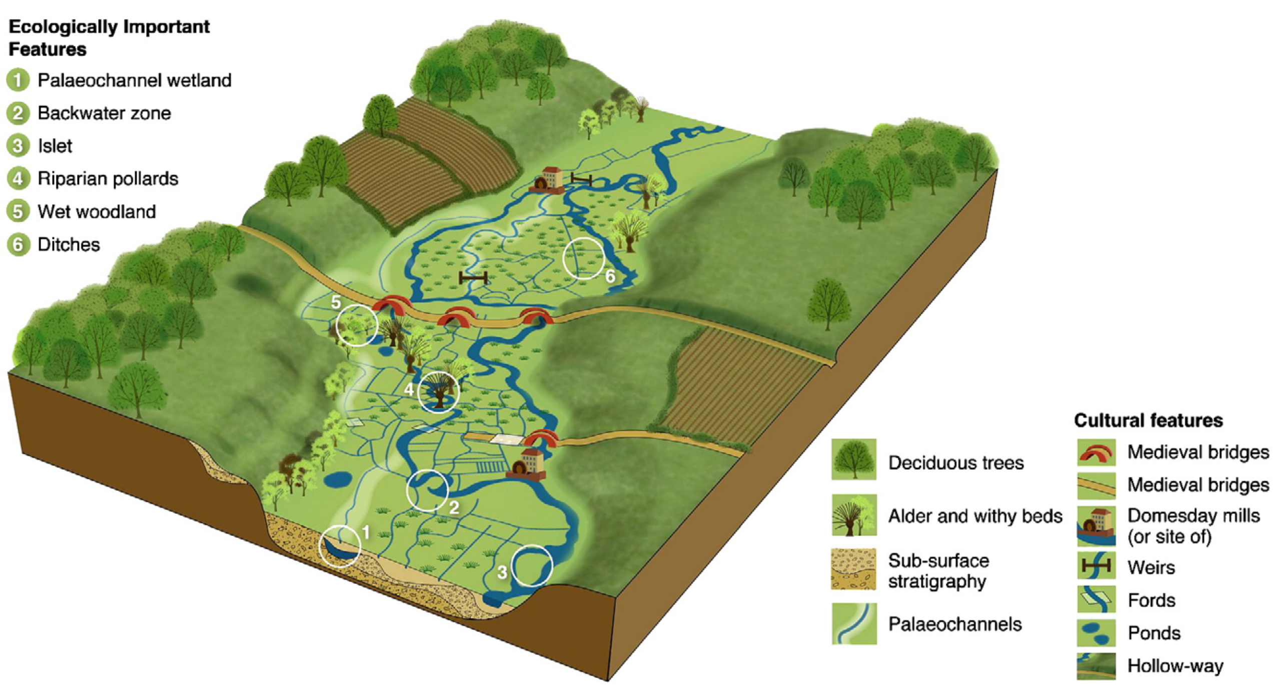

Fig. 2. A schematic representation of a fluvio-cultural unit (FCU) taken from assemblage elements of from the River Avon in Hampshire, UK. See text for elaboration.

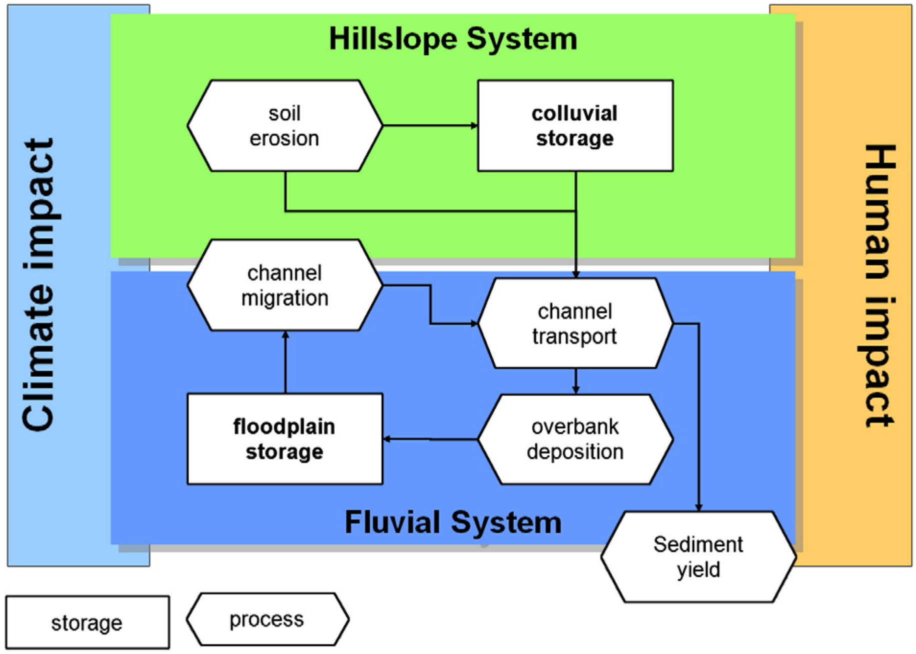

Fig. 3. Major components of long-term sediment budget at the catchment scale.

Ge = gully erosion and deposition
Ce, Cs = creek erosion (including bank and bed erosion) and deposition and
RIVe, RIVs = river erosion and deposition.

Due to scale effects of erosion, transport and deposition of sediment not all components need be considered for every catchment size. In large catchments, in general only sheet erosion (E), colluvial and floodplain storage (S_C, S_F respectively) and sediment output (SY) are considered, simplifying the above sediment budget equation to:

$$SY = E-(S_C + S_F).$$

Catchment wide sediment budgets allow a consideration of differential response to land use and climate impacts and to evaluate non-linear feedbacks within the fluvial system that are not accounted by long-term stratigraphical analysis. To link changing sediment fluxes to their causes, independent time series of land use and climate changes need to be documented. Good examples of the long-term reconstruction of spatially distributed land use changes in the Rhine catchment are given by Zimmermann et al. (2004) and Houben (2008). Based on the spatial distributions of archaeological sites, population densities and agricultural areas were estimated for different archaeological periods. Population densities between the archaeological periods were interpolated by the correspondence analysis of pollen diagrams (Lechterbeck, 2008; Lechterbeck et al., 2009) to obtain a time series of land use impact in certain regions of the Rhine catchment.

With respect to the major LUCIFS objectives, sediment budgets are a effective tool to study land use and climate impacts and internal dynamics in fluvial systems and to bridge the gap between the short-term process understanding and the long-term impact of geomorphological processes under changing external conditions (Lang et al., 2003a,b). Traditionally, small to medium scale studies incorporate hillslope erosion and colluvial and alluvial deposition as the major budget components (Phillips, 1991; Houben, 2006; Seidel and Mäckel, 2007). In general, the higher the spatial and temporal resolution and the shorter the response time of fluvial systems, the more straightforward the connections between changes in land use and climate become. As an example, the temporally resolved Holocene sediment budget for the Belgian Nethen catchment (55 km^2; Verstraeten et al., 2009) distinguishes three periods (early Holocene — 500 BC, 500 BC–1000 AD, 1000 AD–present), which are characterised by continuously accelerating erosion (and sedimentation) rates. These accelerations in erosion can be related to the intensification of anthropogenic land use. However, it has also been noted that sediment yields may not alter significantly following reduced erosion. For example, in the Coon Creek Basin (Wisconsin, USA), Trimble (1999) constructed sediment budgets for three periods (1853–1938, 1938–1975 and 1975–1993) linked to the period of intensified agriculture since the colonisation of European settlers. Even though soil conservation measures decreased soil erosion by a factor of three from 1853 to 1993 AD, sediment yields did not change significantly during that time. The findings of numerous sediment budget studies (Houben, 2006; Seidel and Mäckel, 2007; de Moor and Verstraeten, 2008; Notebaert et al., 2009) suggest a high variability of sediment sources, sinks, and fluxes, as well as complex internal dynamics of river basins.

The magnitude, timing, and duration of channel and floodplain response to land use and climate change are strongly dependent on the residence time of sediment in different sediment stores (Dietrich et al., 1982), which in general increases with the distance between sources and sinks and therefore the spatial scale of the fluvial system (Dearing and Jones, 2003; Walling, 2006). While it is generally accepted that the link between external impacts and the response of the fluvial system becomes less clear with increasing catchment size, our integrated picture of the mechanisms that control the internal dynamics and the buffered response in large scale river basins is incomplete. This fact mainly results from simplified sediment budget concepts and the low temporal and spatial resolution that underlie large scale sediment budgets. Exceptions of long-term and large scale budgets have been published for the well studied Rhine catchment (Erkens et al., 2006; Hoffmann et al., 2007). The results from the Rhine suggest that even at large spatial scales there is a clear increasing trend of floodplain sedimentation and therefore sediment flux during the Holocene. Based on the sediment budget of the Lower Rhine and the Rhine delta, Erkens et al. (2009) calculated the trap efficiency (defined by the amount of sediment trapped in floodplains in relation to the sediment that flows through the river channel) and the amount of sediment reworking of the floodplains of the Lower Rhine. The constant trap efficiency of 15% suggests that increasing sedimentation in the Rhine delta was not caused by changing internal dynamics but might have been caused by increasing human impact during the Holocene. However, in general the increased sedimentation rates on floodplains cannot be unequivocally linked to a cause–effect relationship between human impact and changing sediment fluxes at these scales. Interestingly, for the upper Mississippi valley, Knox (2006) presents a graph also illustrating increased sedimentation rates during the Holocene. The increase is most dramatic for the period post dating European agriculture but nevertheless rates do show an increasing trend before this major human impact (see Fig. 4, p292, Knox, 2006).

2.3. Biogeochemical fluxes

The previous section looked at the long-term quantification of sediment budgets, however, it is also important to note that the same processes of sediment mobilisation, transport and deposition represent a key component of the global biogeochemical cycle through the transfer of sediments from continents to oceans (Meybeck, 1993; Leeder, 2007; Dürr et al., 2009). In this context it is important to recognise that the carbon and nutrients associated with the sediment loads transported by rivers commonly represent a large proportion of the total flux of those elements (Martin and Meybeck, 1979; Meybeck, 2003; Battin et al., 2008). As a result of the intensive use of fertilisers, nutrient levels (P and N) strongly increased (locally up to 50 times, compared to natural levels) alongside sediment and C (Meybeck, 1982).

Although it is now generally accepted that the contemporary land–ocean sediment flux is of the order of 15 Gt year^{-1} (Walling and Webb, 1996; Panin, 2004; Syvitski et al., 2005) and that the equivalent particulate organic carbon (POC) flux is about 0.2 Gt year^{-1} (Beusen et al., 2005), it is clear that these values have changed over time during the past few millennia in response to both land use and climate change (Fig. 4, Walling, 2006). Equally, associated changes in the intensity of erosion, in sediment sources and in the efficiency of sediment delivery can be expected to have caused significant changes in the carbon and nutrient content of the sediment, further contributing to changes in the global biogeochemical cycle. In the absence of instrumental records of erosion rates and sediment fluxes, and associated carbon and nutrient content, extending back more than about 50 years, combined with a lack of such records for many areas of the world, the potential for reconstructing past biogeochemical fluxes provided by the LUCIFS sediment budget approach must be seen as particularly important. To date, there have been few attempts to reconstruct changes in sediment biogeochemistry, the majority of studies have focused on using mine waste contaminated sediments as chronological markers (e.g. Macklin and Lewin, 1989; Thorndycraft et al., 2004). However, the existing work on reconstructing sediment fluxes provides clear evidence of the potential perturbations involved, which in turn have important implications for nutrient and carbon fluxes.

Of particular interest in terms of current scientific debates is the role of soil erosion within the global carbon budget (Kuhn et al., 2009). Lal (2004) states that selective erosion of organic C and its subsequent mineralization during transport and storage represent a major source of atmospheric C. In contrast, van Oost et al. (2007) present data on erosion and deposition rates that support the evidence for an erosion-induced sink of atmospheric carbon equivalent to approximately 26% of the carbon transported by erosion. At the catchment scale, few studies have analysed the carbon storage in floodplain deposits (Walling et al., 2006; Hoffmann et al., 2009b). While these studies generally assume that floodplains are long-term carbon sinks, little is known about the residence time of carbon in floodplain deposits. Resolving these uncertainties and obtaining a better understanding of the fate of sediment-associated carbon and its impact on the global carbon cycle requires integrated investigations of carbon and sediment fluxes at the catchment scale (Stallard, 1998; Kuhn et al., 2009).

Contaminants, especially heavy metals, are not only transported in dissolved phase, but can be bound to sediment particles in the river (Macklin and Lewin, 1989; Miller, 1997). Contaminants, therefore, are transferred through the river system and can accumulate on floodplains, which function as contaminant sinks (Marron, 1992). As a result, contaminants may remain within the fluvial system for a long period of time, even after the original source of contamination no longer exists. Consequently, changes in metal load delivered from the fluvial to the coastal zone may show considerable time lags when compared to anthropogenic release into the fluvial system. Reconstructing past contamination from the fluvial archive, using dated sediment records from the period before and after the beginning of river contamination, therefore offers a great opportunity to define the baseline conditions of contaminant transport in rivers. Lakes, reservoirs, floodplain lakes and overbank sediments are excellent archives from which trends of past river contamination can be determined (e.g. Middelkoop, 2000 for the lower Rhine River, Fig. 5). During the past 100 to 150 years many rivers have become severely contaminated, with maximum pollution occurring during the 1930s and 1960s. Over the past decades, a substantial decrease in metal release into the fluvial system has been achieved in West-European rivers due to improved wastewater treatment and the introduction of standards and legislation (Middelkoop, 2000).

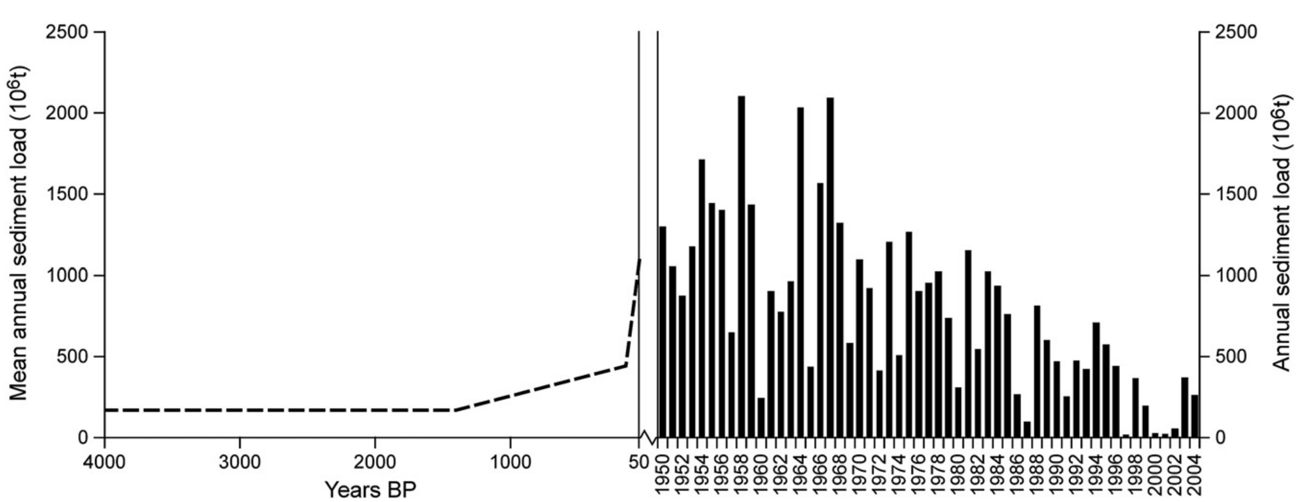

Fig. 4. Recent changes in the annual suspended sediment load of the Lower Yellow River (1950–2004) and a tentative reconstruction of the longer-term trend in the annual suspended sediment load of the river over the past 4000 years (50–4000 years BP), based on Walling (2008) and information presented by Milliman et al. (1987), Saito et al. (2001) and Xu (1998).

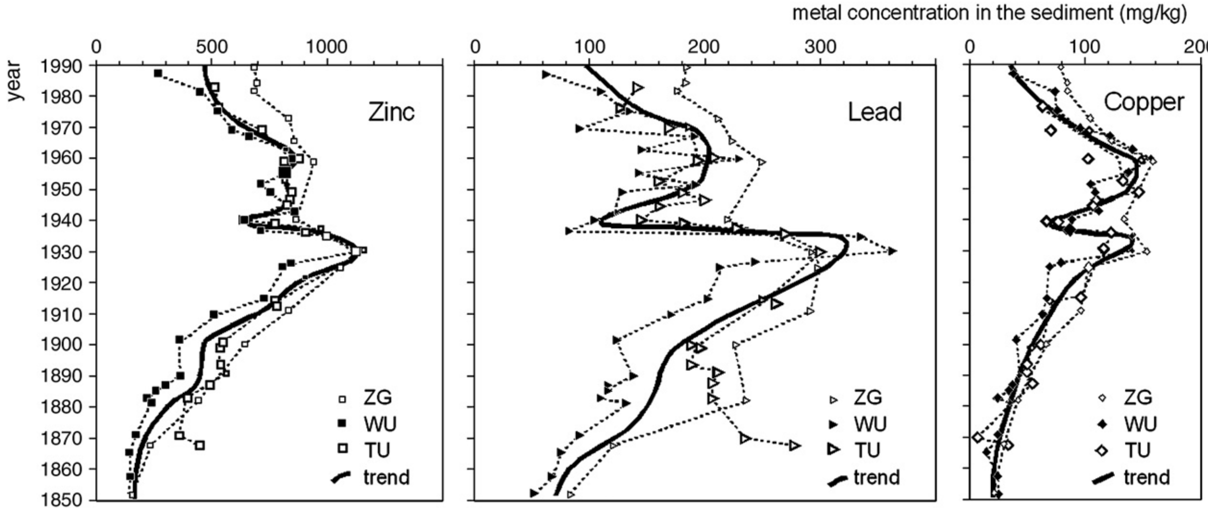

Fig. 5. Trend of heavy metal concentrations in sediment deposited by the lower river Rhine on its floodplains over the past 150 year. ZG, WU and TU refer to floodplain ponds where samples were taken (Middelkoop, 2002).

2.4. Flood magnitude and frequency

So far we have highlighted trajectories of change in river systems, particularly those associated with natural and anthropogenic variations in sediment load. This section focuses on flooding and in particular how the magnitude and frequency of floods may respond to both climate change and the long-term change to sediment budgets. One method of obtaining information on extreme events over longer time periods is through the application of palaeoflood hydrology, defined as the reconstruction of flood magnitude and frequency over centuries to millennia using geomorphological evidence (Baker et al., 2002). The most reliable form of evidence are slackwater flood deposits preserved in narrow bedrock canyons (Baker and Kochel, 1988; Benito et al., 2003) where, in contrast to alluvial reaches, the channel position is stable over longer time periods and floodwater elevation is more sensitive to changing discharge (Fig. 6). This enables robust palaeodischarge estimates calculated using step-backwater hydraulic models, such as HEC-RAS (Webb and Jarrett, 2002), where discharges are routed through surveyed study reaches and are determined by matching the computed floodwater elevations to the mapped slackwater flood deposits — thus providing a minimum discharge estimate for the flood.

The value of palaeoflood hydrology can be illustrated using two contrasting case studies from NE Spain and central India. In both studies the rationale for the research was to place recent catastrophic events within the long-term perspective of flooding over the last millennium. In the Llobregat basin in NE Spain the largest instrumental

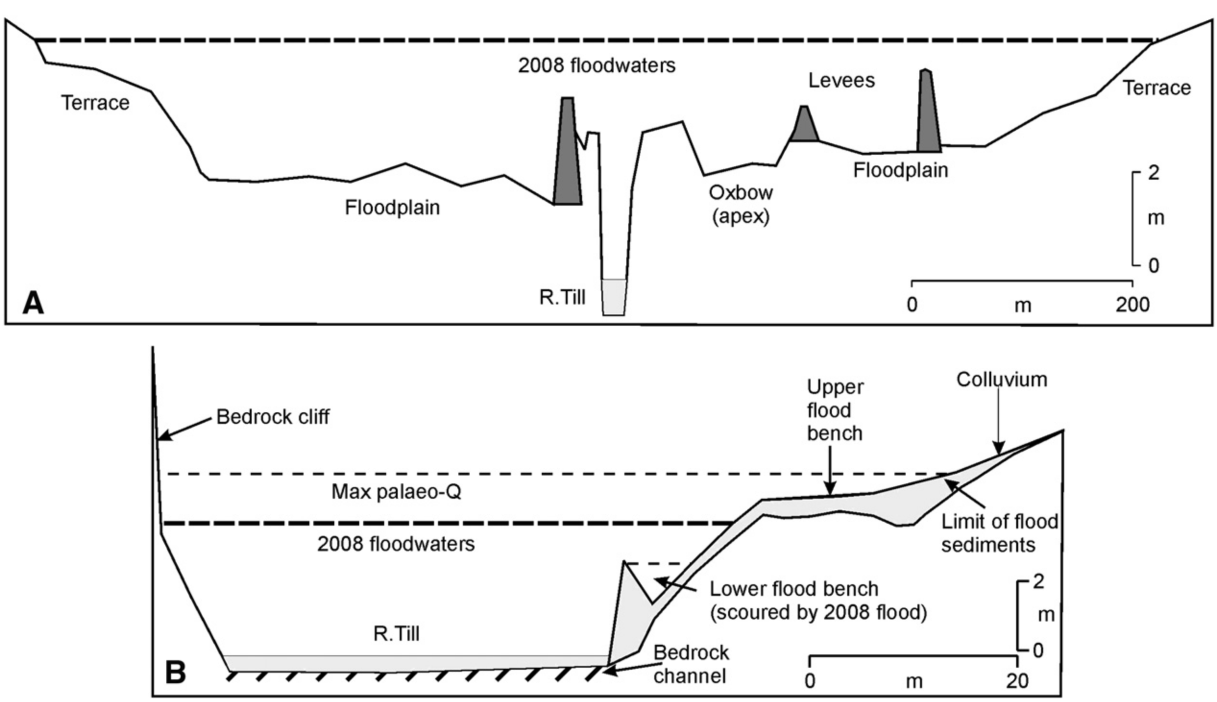

Fig. 6. Valley cross-sections of the River Till (northern England) illustrating the floodwater levels of the September 2008 flood at A): a wide alluvial reach; and B) a narrow bedrock reach. The figures illustrate the increased sensitivity of floodwater elevation to flood discharge (and flood geomorphological features) within the bedrock reach, with evidence for larger floods in the past preserved in the upper flood bench. This suggests that in the long-term history of the Till, the 2008 flood was not so exceptional despite being the largest on record and flooding the alluvial floodplain with over 3 m of water, in the process submerging the flood defence levees and Late Pleistocene terraces. Unpublished data (V.R. Thorndycraft).

flood (2300 m^3s^{-1}) occurred in 1971, however, sedimentary evidence at Monistrol de Montserrat indicated that an extreme flood of >4680 m^3s^{-1} occurred during the interval cal. 1515–1640 AD (Thorndycraft et al., 2005). Correlation with documentary flood records strongly suggested that the flood in question was the November 1617 event. Further analysis of archival evidence and palaeoflood sites on nearby rivers enabled a detailed reconstruction of the climatic causes of this event, its magnitude across the region and its socio-economic impacts (Thorndycraft et al., 2006). It appears that the 1617 flood was one exceptional event during decadal scale periods (AD 1580–1620; 1750–1780; 1830–1860) of increased flood magnitude and frequency during the Little Ice Age (LIA) (Llasat et al., 2005). Upstream at the Pont de Vilomara study site, slackwater sediments preserve evidence of at least 8 events of a similar extreme magnitude, radiocarbon dating indicating that 5 of these occurred during the last 3000 years, two during the colder and wet period of 2850–2600 cal. BP (Thorndycraft et al., 2005).

In central and western India, there is evidence to suggest that monsoonal floods within the latter half of the 20th Century were the largest for over 500 years (Kale and Baker, 2006). For example, the 1970 flood of the Narmada River was recorded at 69,400 m^3s^{-1} and the largest flood on record in the Indian subcontinent, with a magnitude of 99,400 m^3s^{-1}, was generated by the Godavari River in 1986 (Kale, 2007), far larger than any flood occurring since before the LIA. Indeed, palaeoflood evidence from a number of river valleys indicates that the LIA was a period of relatively low magnitude floods (Kale and Baker, 2006) and that it was during the Medieval Warm Period (MWP) *ca.* 800–1000 years earlier when the last extreme monsoonal floods were witnessed (Kale et al., 2003; Kale and Baker, 2006). This research is particularly valuable as it illustrates the response of river systems to changes in monsoon strength. Multiproxy (both continental and marine) archives, such as reconstruction of monsoon rainfall based on $\delta^{18}O$ of a stalactite (Ramesh, 2001), monsoon winds based on % G. bulloides in Arabian Sea (Anderson et al., 2002) and an ice core from Dasuopu, (Thompson et al., 2000) indicate noteworthy weakening of the Indian summer monsoon during LIA (deMenocal et al., 2000; Anderson et al., 2002; Honga et al., 2003). The palaeoflood evidence provides data on basin scale flood response to the impact of varying monsoon intensity, with two contrasting flood populations representing weaker and stronger monsoon circulation (see Fig. 11 in Ely et al., 1996). This clearly has implications for estimating future flood risk and design discharges in densely populated catchments sensitive to monsoonal flooding.

Quantifying the impact of both long-term human land use change (catchment scale) and changing floodplain environments (reach scale) on flood magnitude and frequency is more problematic. For example, to achieve the latter, information is needed on bed elevation, channel dimensions and boundary conditions, including roughness. In unstable alluvial reaches this is often difficult to obtain, however, some case studies have been successful. For example, in the Upper Mississippi Valley Knox (2006) was able to reconstruct channel dimensions going back to the onset of settlement and agriculture due to: 1) the long-term stability of the channel bed due to Holocene flows not having the competence to incise the Late Pleistocene basal gravels; and 2) the distinctive stratigraphic marker of post-agricultural floodplain alluviation, as observed in other basins of the USA (e.g. Costa, 1975; Trimble, 1999; Walter and Merritts, 2008). Knox (2006) demonstrated an increase in channel capacity that in some cases eliminated overbank flooding. In terms of flow hydraulics, this change resulted in increased bank base shear stresses, estimated for the Strickland Branch tributary as increasing from 64 Nm^{-2} in 1832 to 92 Nm^{-2} around 1890 and 140 Nm^{-2} since the early 1940s (Knox, 2006). It is probable that there have been similar types of impacts in European rivers over longer-term timescales.

2.5. Database and analysis tools

For river management to benefit from existing data on long-term fluvial system response there is a need for the design of appropriate databases and analysis tools (Brown, 2003). This has been achieved for instrumental data, for example the European Water Archive developed by the FRIEND programme (Flow Regimes from International Experimental and Network Data) that contains flow data for around 4000 gauge stations across 30 countries (Servat and Demuth, 2006). Equivalent databases for pre-instrumental data are more fragmentary and the nature of the information to be included is more difficult to determine primarily in terms of incorporating the longer temporal period and associated dating and palaeohydrological errors. The GLOCOPH (Global Continental Palaeohydrology) commission of INQUA has taken the lead in the creation of palaeohydrological databases, starting with the approach of Branson et al. (1996) that collated detailed information on a case study basis. Data were organised according to basin characteristics; channel planform; channel sediments; and palaeohydrological reconstructions (e.g. discharge and stream power). The recent improvement in GIS capabilities has enabled greater sophistication in terms of data analysis. From a research perspective the palaeoflood GISs created in Spain, PaleoTagus (Fernández de Villalta et al., 2001) and SPHERE-GIS (Casas Planes et al., 2003), were considered a success as they combined palaeoflow data and socio-economic impacts of historical floods in a GIS environment to create an effective management tool. However the use of these GISs in regional flood management has been less successful, reflecting the paradigm lock between research and basin management (Gregory, 2004; Thorndycraft et al., 2008). Lewin et al. (2005) developed a radiocarbon database for the UK that collated dates sampled from fluvial environments, alongside information on sedimentary contexts and basin physiography. This enabled a systematic and methodological analysis of the dates using summed probability plots for the UK (Lewin et al., 2005; Johnstone et al., 2006) and other regional databases (Lang, 2003; Starkel et al., 2006; Thorndycraft and Benito, 2006a; Kale, 2007; Hoffmann et al., 2008b; Zielhofer and Faust, 2008). Macklin et al. (2006) argued that distinctive peaks in the summed probability curves were related to an increase in flooding in response to climatic variability. However, caution needs to be taken here because: a) the calibration curve directly influences the probability plots, especially sharp peaks (Fig. 2 in Thorndycraft and Benito, 2006a,b) correlation with climate proxies does not invoke causality, especially in fluvial systems given the varying allogenic and autogenic drivers of change; and c) it is problematic to decipher river response to climate in terms of defining and quantifying fluvial geomorphic activity, individual extreme event magnitude and periods of increased flood frequency. The latter was investigated for the Spanish database through the analysis of dates from slackwater flood deposits in bedrock canyons, where attempts were made to define periods of increased flood frequency by only using dates that bracket sedimentary evidence of multiple extreme events of known magnitude (Thorndycraft and Benito, 2006b).

Improved geochronological models for fluvial sedimentary sequences may be derived through Bayesian statistics of multiple date sequences (Brown, 2008; Chiverrell et al., 2008), as has been applied in other sedimentary environments (Blockley et al., 2007). In the Ribble Valley (NW England), Chiverrell et al. (2008) have used Bayesian analysis to interrogate multiple radiocarbon dates from a suite of alluvial terraces. The results provide a range of scenarios for phases of aggradation and incision and highlight samples that may be out of sequence, for example due to reworking or contamination. Such age modelling approaches add further caution to the interpretation of summed probability plots. Alternatively, Hoffmann et al. (2008a) used a ^{14}C-database of dated overbank deposits to estimate floodplain sedimentation rates in the Rhine catchment. Even though the temporal resolution of this approach is much lower, compared to the summed probability plot, the comparison with results from the Mississippi and the Yellow River gained motivating results regarding the sensitivity of river systems under differential environmental conditions.

2.6. Complex response and non-linearity

The modelling and prediction of fluvial systems is difficult as their behaviour is often complex and highly non-linear. Prediction may also be hampered by rivers and floodplains acting as sediment stores. Instead of being transmitted to the basin outlet, sediment may accumulate on floodplains or features such as alluvial fans, only to be released when re-eroded some significant time after. As already noted above this occurs over a range of time and space scales and may lead to considerable time lags between causes and effects up to several 1000 years (Church and Slaymaker, 1989).

At short time scales, rivers often show considerable variation and path dependency (hysteresis) in the relation between water discharge and sediment transport. For example, Cudden and Hoey (2003) report variations over three orders of magnitude in bedload flux from a glacial stream, despite relatively constant water discharges. Suspended sediment concentrations in large rivers often show strong hysteresis (Bogen, 1980), depending on sediment availability in the source areas and antecedent discharge conditions (Asselman, 1999; Doomen et al., 2008). At the catchment scale, this behaviour was first identified by Schumm (1977) with his experiments and theories of complex response. These non-linear responses mean that similar inputs (e.g. storm events) can cause quite different results. For one flood part of a channel may incise and another deposit, yet for a subsequent flood of similar size the response may be quite different. This is due to the presence of thresholds within fluvial systems. For example fluvial processes such as bed armouring can lead to selective transport and conditions such as equal mobility (Andrews, 1983) where small increases in erosional power at the bed of a river can lead to almost all the bed material being entrained. Other examples include landslides, and bank erosion, where there may be a critical angle of repose above which a slope (or river bank) fails.

Over long time scales, sequences of river terraces and fossil channel patterns are often considered to reflect river adjustment to changes in climate and land cover (e.g. Knox, 1996; Huisink, 1997; Tebbens and Veldkamp, 2000; Knox, 2001; Starkel, 2002; Gao et al., 2007). However, autogenic controls (intrinsic behaviour, complex response) and the inheritance of morphology and sediments over time make this response very complex. Erkens et al. (2009) demonstrated for a succession of Late-glacial and Holocene river terraces in the Upper Rhine Graben that Late-glacial climate warming triggered channel incision, coinciding with a transition to a meandering river pattern: a climate-dominated forcing with a slightly lagged response. However, subsequent terrace formation during the Holocene was not controlled by climate forcing; instead, intrinsic controls, such as continued incision, a decreasing gradient, autogenic evolution and a high preservation potential are a plausible cause of the presence of this terrace sequence.

Processes operating at shorter time scales may have important consequences for the longer-term development of fluvial systems. Kleinhans et al. (2008) demonstrated that the morphodynamics (position and downstream migration of meander bends, and associated channel riffle-pool bar topography) and the division of sediment on a timescale of decades to centuries are major controls of the occurrence of avulsions (the abandonment of an old river channel and the creation of a new one) and life-times of bifurcations (where a river divides in two channels) in river deltas. Consequently, the decadal pace of these controls influence on the long-term the avulsion frequency within deltas in the course of millennia, and hence their resulting alluvial architecture.

The main problem non-linear behaviour presents to researchers examining the fluvial archive is that it makes it especially difficult to link cause and effect — for example to relate a stratigraphic unit to a particular flood event or time. Numerical sediment flux models have suggested that some fluvial systems display the key symptoms of self organised criticality, which if true, would make them effectively unpredictable (Sidorchuk, 2006; Coulthard and Van De Wiel, 2007; Van De Wiel and Coulthard, 2010). However, one way in which we can begin to explore this non-linear response and to understand what may control fluvial response is through a combination of 1) reconstructions of external impacts (climate and land use), 2) empirical sediment budgets that integrate high-resolution and well-dated sedimentary records and spatial analysis of budget components at the catchment scale, 3) laboratory experiments and 4) numerical modelling. Predictive models to simulate the response of rivers to changing environmental conditions should consider the internal mechanisms within the system, operating over a range of scales.

3. The future research agenda

3.1. Explorative and predictive modelling of fluvial systems

Whilst it is always attractive for numerical modellers to try and predict what may occur in actual catchments this can be difficult given the non-linearities and thresholds described in the previous section. An alternative approach is to use numerical models in an exploratory and heuristic way, to create and test research hypothesis and to thus understand how systems operate. Examples of this approach include the cellular braided river model of Murray and Paola (1994) where their parsimonious representation of a braided river showed that the only factors required for braiding were erosion and deposition, and a laterally unconstrained environment. Similarly, earlier landscape evolution models showed how river catchments balance tectonic uplift and erosion to establish a state of dynamic equilibrium (Willgoose et al., 1991; Tucker et al., 2001) or how the addition of a simple threshold for fluvial erosion led to a completely different landscape form (Howard, 1996). Such exploratory models may appear abstract or irrelevant to many landscapes, but they have helped us understand how rivers and landscapes interact.

Another strength of this approach is the possibility to link the results to physical flume based models. There have been several studies with experimental models of drainage basin evolution (Hasbargen and Paola, 2000; Hancock et al., 2006) and linking vegetation with fluvial dynamics (Coulthard, 2005; Bocchiola et al., 2006; Tal and Paola, 2007). While the parallels between these simple physical models and numerical codes are great, a better representation of the complex and non-linear reality is still needed (Murray et al., 2009).

One of the main difficulties with modelling long-term sediment budgets and fluvial geomorphology is validation. Numerical models are capable of providing highly detailed (spatially and temporally) data on landscape form (through a DEM) or other metrics such as sediment discharge or yield. However, to validate such models we need long records of measurements, preferably with an adequate spatial coverage. However, for modelling fluvial development over time scales of centuries to millennia, this would ideally require high-resolution records of water and sediment, snapshots of topography or channel pattern stretching back 10 000 years, which is problematic. Therefore, we must find alternative indicators and proxies of fluvial development. These may include landscape metrics such as hypsometric curves, or ratios of contributing drainage area and elevation (Hancock et al., 2006), or using histograms of merged radiocarbon dates as a proxy for 'alluvial activity' (Coulthard and Macklin, 2001; Coulthard et al., 2005). This is where the strength of experimental modelling lies — in its more qualitative rather than quantitative nature.

The issues with model validation, and the strengths of models for exploratory modelling imply that numerical models currently have little worth for predictive modelling. Indeed, given the non-linear nature of river systems it would be very difficult to predict where an eroding channel bank may lie in 100 years. However, existing numerical models could be used to suggest whether or not a particular section of a river is likely to be eroding or remain stable; or whether it will remain a single channel or switch to a braided state. Modelling fluvial systems is in many ways as complex and as unpredictable as climate and meteorological modelling. Therefore we should shift our expectations from that of an engineering perspective (where, when and by how much things will happen) to that of a geomorphologist (what the dynamics or overall behaviour will be). We should not expect models to predict precisely, but to give general trends. Borrowing from the expertise of climate modellers, this could involve using a suite of multiple (including Monte Carlo) simulations with slightly different starting and running parameters and establishing what the average — or overall trend is from all the simulations.

In addition to this, predictions from numerical models will improve, due to advances in model development and process representation. Increases in computing power will allow increased complexity in models, possibly so that processes such as turbulence can begin to be included in long-term simulations of fluvial systems. Finally, parallel processing may well offer a route for improving model predictions (as it has for climate modelling). So, the issues facing predictive modelling of fluvial systems should be seen as challenges rather than problems.

3.2. PHAROS — a common framework for data integration

With improving technology in GIS, topographic (e.g. LIDAR) and subsurface surveys (e.g. GPR), reviewed by Brown et al. (2009a), efforts should be dedicated towards developing more sophisticated datasets within the LUCIFS program that combine: 1) contemporary and long-term hydrological and geomorphological information (e.g. long-term time series of water, sediment, C and P fluxes with associated errors); 2) DEMs of contemporary floodplain topography and land use (based on LIDAR and on high-resolution satellite images); and 3) reconstructed DEMs of palaeofloodplain environments. Such tools, in combination with modelling approaches, would enable more effective river management in terms of improving the ability to identify flood risk, susceptibility to erosion and potential catastrophic channel change. Whilst the LUCIFS program provides a framework for such data collation there is also the potential of added value from data exchange with other international research programs. Within PAGES-PHAROS the goals of the HITE and LIMPACS research programs are to integrate long-term information on land cover (HITE), water quality and biodiversity (LIMPACS). These aims complement those of LUCIFS, so to provide a comprehensive understanding of past climate, human and ecological interactions, synergies between the three research programs should be investigated. For example, long-term land cover records at the basin scale could be particularly valuable for helping decipher causal mechanisms of change in fluvial systems. Therefore, in addition to the compilation of key datasets within the separate research programs, efforts should be made to: 1) coordinate exchange of knowledge and research experience between the programs; and 2) identify key regional case studies where future integrated multidisciplinary research projects will lead to value added deliverables (Fig. 1).

4. Conclusion

The LUCIFS strategy implemented over the last decade, with its focus on i) a global regionalisation of the key controls influencing water and sediment fluxes, ii) the completion of in-depth case studies, and iii) integrated catchment modelling (Wasson, 1996), has led to greater progress in our understanding of the response of fluvial systems to Holocene global change. In this paper we have reviewed the current state of knowledge with regards quantifying long-term sediment fluxes (and associated nutrients such as C, N and P) and fluvial regimes, including the response of extreme events to climatic variability. This review has enabled key gaps in knowledge to be identified. We propose that future research strategies should focus on: 1) synthesising the data available from existing case studies (compilation of a meta-database); 2) targeting research in data-poor regions; 3) integrating sediment, C, N and P fluxes; 4) quantifying the relative roles of allogenic and autogenic forcing on fluvial regimes, extreme events and sediment fluxes; and 5) improving long-term river basin modelling. Added to these research aims, the LUCIFS scientific community should collaborate more fully with other groups within PAGES-PHAROS, namely HITE (Human Impact on Terrestrial Ecosystems) and LIMPACS (Human and Climate Interactions with Lake Ecosystems) to foster improved, and mutually beneficial, knowledge transfer. Furthermore, to enable improved river basin management there needs to be greater cooperation between the scientific research and environmental management communities.

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