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Review Article

Integrated catchment assessment of riverine landscape dynamics

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Abstract. The traditional approach to study riverine environments focuses on the river reach scale, with streamflow as a steady state driving force. Here, the accent is on the dynamic nature of streamflow. Impacts of the hydrological regime, of floods and streamflow variability, on riverine landscapes are reviewed. To evaluate such impacts, it is necessary to focus on the entire catchment in an integrated fashion, so that local changes in river morphology and river habitat can be evaluated in context with upstream catchment processes. A framework for an integrated physically-based catchment modelling system, based on models of hydrology, hydrodynamics, sedimentology and ecology, is presented. The hydrological element addresses runoff response in a catchment on a continuous basis in time and distributed in space, while the hydrodynamic, sedimentological and ecological elements address the interactions and feedbacks between water, sediment and the ecosystems at the scale of the river corridor. The models are arranged in a nested fashion, with long-term quantification of catchment and river system dynamics as the main objective. A long-term vision of catchment processes is important for the evaluation of potential anthropogenic influences and climate change effects, as well as for the evaluation of river conservation projects.

Key words. Hydrological regime; floods; catchment analysis; modelling; riverine landscape.

Introduction

Streamflow plays a central role in shaping the physical and biological environments of riverine landscapes. Local disturbances, for instance by flood-induced erosion, redistribution of sediment or accumulation of debris, may lead to severe habitat changes. It is also recognised that periods with low flow or, more generally, streamflow variability are crucial for habitat recovery (e. g., Minshal, 1988; Resh et al., 1988; Poff and Ward, 1989; Poff, 1996). All of these elements constitute the natural hydrological regime as a determining factor for riverine ecosystems (Poff et al., 1997).

One of the fundamental challenges in hydrology and ecology is the evaluation of the soil-vegetation-climate interactions and feedbacks as they pertain to ecosystems, at different spatial scales. The natural hydrological regime is a product of such complex interactions on a catchment scale. The onset of changes in the physical environment of rivers is often dictated by these interactions. As a result, local changes in river morphology as well as river habitat are connected with large-scale catchment features such as climate, geology, topography, and catchment response in general. This continuity is especially crucial for assessing long-term catchment and ecosystem dynamics, and for investigating the role of heterogeneity

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and variability in channel characteristics and river habitat (e.g., Montgomery, 1999).

The temporal and spatial variability in channel processes and features control how biological communities respond to changes in the physical river environment. In this regard, two important concepts of connectivity between rivers and habitat have been developed: the river continuum concept, which addresses the role of longitudinal connectivity in river systems (Vannote et al., 1980), and the flood pulse concept, which addresses the lateral connectivity between processes in the river and floodplain (Junk et al., 1989; Tockner et al., 2000). However, these approaches focus on the river system per se, and do not consider the dynamics in the context of catchment processes and changes (Montgomery, 1999).

This review paper explores the *catchment perspective* as a basis for studying the physical linkages between precipitation, runoff, and riverine ecosystems on a continuous long-term basis. An integrated physically-based catchment modelling framework, which consists of nested hydrological, hydrodynamic, geomorphological and ecological models, is discussed as a foundation for assessing and quantifying long-term changes in the river environment. The role of sediment dynamics is especially stressed, as it is considered fundamental for riverine landscapes (e.g., Carling, 1995; Lane et al., 1996). It is argued that a long-term vision of catchment processes is important for the evaluation of potential anthropogenic influences and climate change effects which may impact the natural hydrological regime, in particular extreme events, with outstanding effects on the river environment. A long-term perspective is also important for catchment monitoring and the evaluation of river conservation and rehabilitation policies and measures.

The paper is organised in three sections. In the first section, the dominant catchment features and processes are identified. The second section reviews the role of the hydrological regime, in particular of floods and streamflow variability, in shaping the physical environment of riverine landscapes. Potential impacts of anthropogenic and natural changes on the dynamic hydrological regime are discussed. In the third section, the catchment modelling framework is outlined, and some main problems and challenges are reviewed.

Integrated catchment assessment

The catchment is considered to be a natural landscape unit because it provides spatial and temporal continuity in fluxes of matter and energy (e.g., Petts et al., 1995). These fluxes (e.g., of water and sediment) are a fundamental part of the physical and the biological environment of river systems. The catchment can be conceptually divided into three regions: the headwater basins, the low-order stream system, and the main river corridor (Fig. 1). These regions are connected by fluxes of water $q_w(s,t)$ and sediment $q_s(s,t)$ that are variable in space s and time t, and are determined by climate and land surface characteristics. The dominant processes that affect the physical riverine environments are also space and time dependent, and range from short-term response to floods, to long-term evolution of the riverine landscape. Different process domains can be identified within a catchment (or region) with distinct influences on lotic and riparian ecosystems (Montgomery, 1999).

The scheme in Fig. 1 illustrates that changes in the river environment at a site depends not only on local conditions, but also on large scale regional and catchment characteristics (e.g., climate, topography, soil, vegetation). As a result, long-term changes at a site can only be evaluated in relation to the long-term dynamics of water and sediment in the upstream catchment (integrated catchment assessment).

What are the dominant catchment characteristics and processes at the different spatial scales in relation to riverine ecosystem dynamics? *Headwater basins* are the areas of the most dynamic response to intense rainfall (e.g., Poesen and Hooke, 1997; White and Garcia-Ruiz, 1998). Hillslope erosion and mass movement (landslides, debris flows, mudflows, etc.) may supply large quantities of sediment (fine and coarse) to downstream river sections (e.g., Edwards and Owens, 1991). Topography, vegetation cover and soil properties are the crucial variables for runoff production and erosion. *Low-order streams* (according to the Horton-Strahler classification; Strahler, 1957) are generally high gradient streams with variable flow conveyance, riparian vegetation encroachment, highly variable surface roughness, and often with geological controls on channel development. Erosion or deposition occurs locally, depending on the supply and type of sediment, the erodibility of the surface, and flow magnitude (e.g., Lane et al., 1996; Wohl, 2000). In the long-term, channel shape generally adjusts to dominant flow conditions. In the downstream *main river corridor*, which contains both the main channel as well as the floodplain, the dominant processes are flood and sediment conveyance. The gradient of the streams is generally low. River-floodplain interactions are important for overbank flows. However this is only a conceptual division, since in most natural rivers distinct transitional regions exist where, for example, characteristics and typical responses of both low-order streams and main channels coexist.

An integrated catchment perspective is therefore required to understand the physical environment at all spatial scales. This is well illustrated in an example of the observed distribution of erosion patterns produced by a single extreme rainfall and flood event in the Versilia and Turrite River basins (Italy, 1996, Fig. 2). Although the

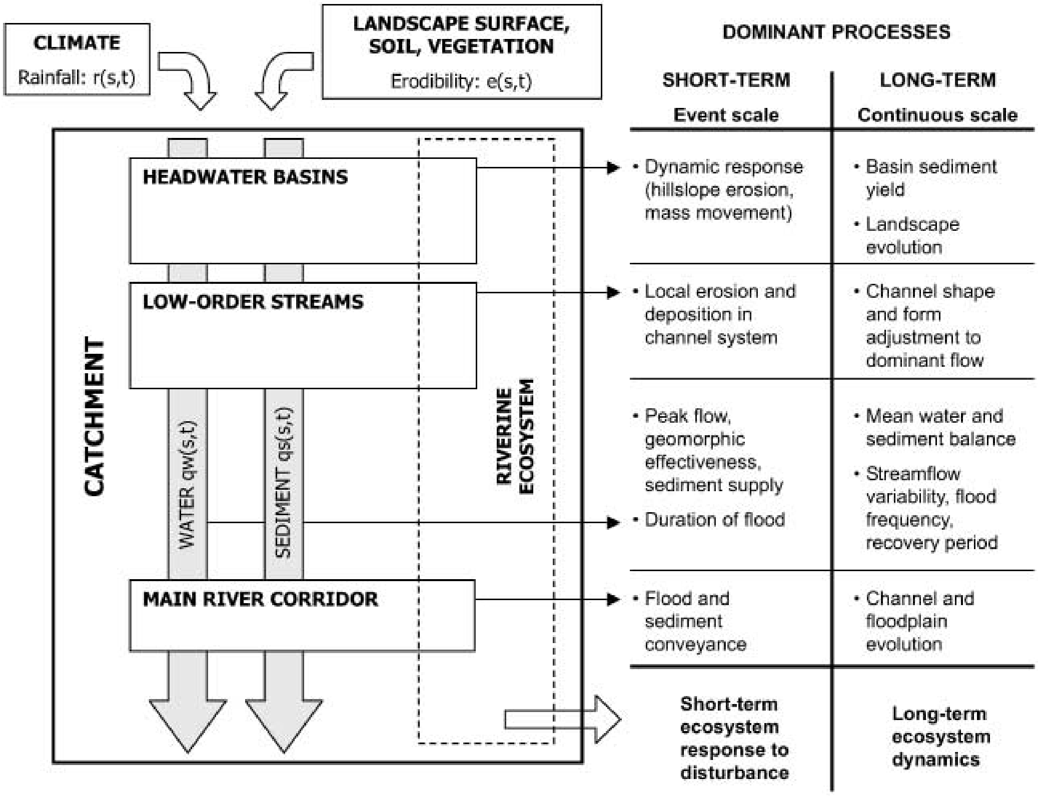

Figure 1. Schematic model of catchment response with the dominant processes in the physical riverine environment at a short-term and long-term timescale.

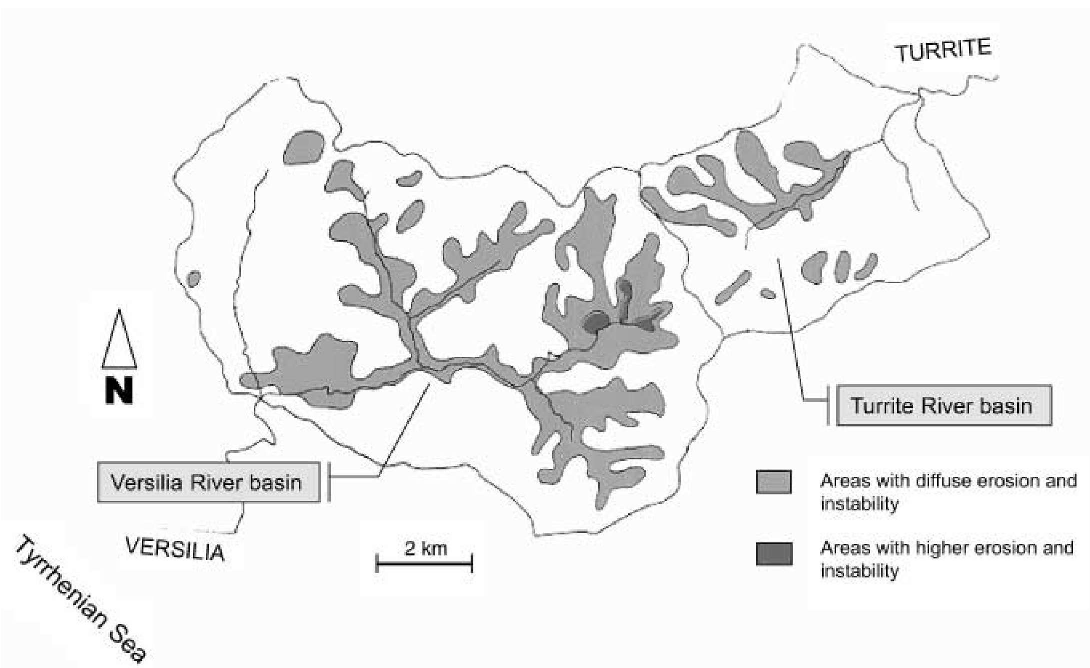

Figure 2. Map of slope erosion observed after the flood event on 19 June 1996 in the Versilia and Turrite River basins, Italy. The upper part of the Versilia basin ($A = 70$ km^2, elevation range ~ 300–2000 m a.s.l.), which includes the areas affected by surface erosion and slope instability, is covered by broad-leaved forest (~ 73%) and pasture (~ 12%). Eroded areas are generally characterised by slopes higher than 30°. The map does not display channel erosion (modified after Rosso and Serva, 1998).

most severely eroded areas were confined to steep headwater basins, channel changes, which significantly altered the river environment, were observed throughout the entire river system, depending on flood peak and upstream sediment supply (Rosso and Serva, 1998).

The temporal dimension of riverine landscape change is closely connected with the catchment hydrological and sedimentological regime. Studying the impact of individual floods on the river environment has only limited meaning because of unknown or uncertain antecedent conditions in the catchment. To understand long-term channel change it is necessary to study the rainfall-runoff relationship in a catchment and its effects on the river environment on a continuous basis in time, focusing not only on major flood events. In summary, integrated catchment assessment should combine hydrological, sedimentological and ecological analyses, and particularly the feedbacks between them. In order to appreciate the connection between ecosystem dynamics and hydrological regimes, integrated catchment assessment should focus on long-term behaviour.

Hydrological regime at the landscape scale

The hydrological regime of a catchment is a fundamental driving force for riverine landscape change. Two elements of the hydrological regime are of primary ecological significance (Poff and Ward, 1989; Poff, 1996): (1) the nature of a *flood*, particularly its intensity and duration; and (2) *streamflow variability*, i.e., the seasonal cycle of streamflow, including the timing of floods, their recurrence and predictability. Floods are crucial in creating, maintaining or destroying riverine habitats (e.g., Bain et al., 1988; Friedman et al., 1996; Bendix and Hupp, 2000; Richter and Richter, 2000), while streamflow variability controls species diversity, community structure and evolution, as well as the development of riparian vegetation (e.g., Minshal, 1988; Resh et al., 1988; Poff and Ward, 1989; Poff and Allan, 1995).

In terms of the effects of streamflow on the physical environment of rivers, it is important to envision streamflow according to some geomorphically meaningful criteria, such as geomorphic effectiveness (Wolman and Miller, 1960; Wolman and Gerson, 1978; Baker, 1994). Flow magnitude by itself does not provide a sufficient measure of geomorphic change in streams. *Geomorphic effectiveness* can be viewed as a potential landform modification controlled by flow properties (e.g., stream power, flow velocity and depth, turbulence, shear stress) and by the resistance of the fluvial system to change (e.g., critical threshold of sediment motion, roughness, bedrock geology). Assuming that the river environment has adapted to the natural hydrological regime, changes in this regime, especially those exceeding critical thresholds for geomorphic adjustment, may have significant consequences for the riverine landscape (e.g., Schumm, 1973).

Floods

Based on the concept of geomorphic effectiveness, three different types of floods can be defined (Fig. 3; after Costa and O'Connor, 1995). Here it is assumed that geomorphic effectiveness is proportional to the time-integrated unit stream power of a flood above a critical threshold. Unit stream power combines flood duration, flood magnitude, channel gradient, and channel geometry, and is a widely used variable in hydrology and geomorphology (e.g., Bull, 1988; Magilligan, 1992; Miller, 1995). The critical unit stream power distinguishes between thresholds for erosion in alluvial and bedrock controlled channels.

With reference to Fig. 3, *type A* floods have high peaks, but are of very short duration, and thus their geomorphic effectiveness is low. Examples of these types of floods are flash floods in small headwater basins (e.g., Costa and O'Connor, 1995). However, although channelised flow may only lead to geomorphically relatively ineffective floods in headwater basins, surface erosion by overland flow in the form of rill and gully erosion may cause dramatic mass movements with long-lasting effects on the riverine landscape downstream. The effects of these floods on riverine ecosystems are mainly expressed as local disturbances, but also may appear far downstream as a result of large erosional processes.

Type B floods are of longer duration and exhibit significant geomorphic effectiveness. They generally occur in high gradient streams of low stream order. They are

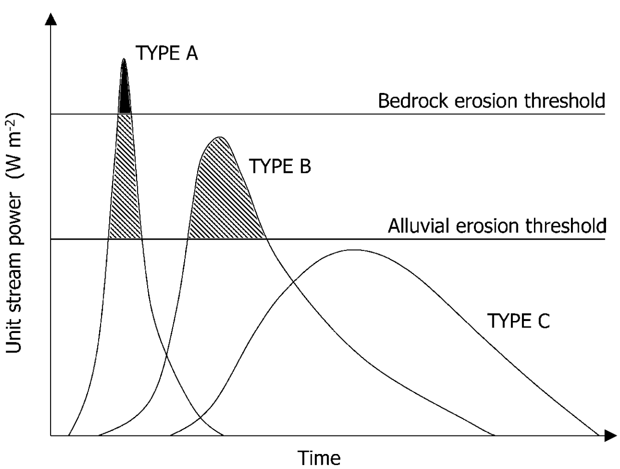

Figure 3. Schematic flood types (adapted from Costa and O'Connor, 1995). Shaded area is proportional to the geomorphic effectiveness of individual floods exceeding a critical threshold for erosion of alluvial and bedrock controlled channels (conceptualised here as the time-integrated unit stream power).

associated with a high erosion rate, dramatic changes in channel shape and form, and the frequent removal of riparian vegetation. Although they may not exceed the critical threshold for channel modification in bedrock rivers, they commonly cause significant geomorphic change in alluvial rivers (e.g., House and Pearthree, 1995; Gutierrez et al., 1998; White and Garcia-Ruiz, 1998). Since scouring is a function of sediment supply, it may be locally interspersed with deposition (e.g., Hooke and Mant, 2000; Sloan et al., 2001). These floods affect the riverine ecosystems in a more diffuse way, although the appearance of the impacts is more similar to a sequence of local disturbances, rather than to a continuous and extensive channel bed disruption.

Type C floods are of long duration but low peak unit stream power. They commonly occur in large lowland rivers with low gradients and generally are ineffective in causing significant channel change. However, they may carry large amounts of suspended sediment supplied by low-order streams, eroded from the main stream channel bed and banks, and from sediment remobilised from the floodplain. Channel change may result from the aggradation and degradation related to sediment transport (e.g., Baker, 1977; Kale et al., 1994).

Channel form and pattern play an important role in the geomorphic response of rivers to floods. For instance, in braided rivers, significant change in channel pattern may result from relatively small floods. During overbank floods in lowland rivers, geomorphic change in floodplains can be more significant than in the channel itself. Sediment size and the gradation of sediment are also important. Channel change in gravel bed rivers is generally longer lasting than in sand bed alluvial channels. Special cases are outburst floods that result from the collapse of natural dams (e.g., moraines, landslides, rock and woody debris jams) or man-made dams. These floods may reach magnitudes far larger than natural floods and cause dramatic channel change (e.g., Pitlick, 1993; Brooks and Lawrence, 1999; Wohl 2000).

It is important to recognise that as floods propagate through the stream system, their effects are amplified or dampened in the downstream direction, depending on the heterogeneity in channel conveyance and the spatial structure of the river network. At the same time the geomorphic threshold for erosion in a catchment is variable in space. Therefore, a flood that is geomorphically effective in upstream areas of the river network, may be less in downstream sections, and vice versa. Furthermore, the magnitude of a flood is dependent on the antecedent soil moisture conditions, the dominant runoff-producing mechanism, and the distribution of precipitation in a catchment, all of which vary spatially (e.g., Michaud et al., 2001). Therefore, every flood situation is different, and detailed comparisons between the effects of single floods should be made with caution.

Streamflow variability

The riverine landscape is also shaped by low and moderate flows. These are important not only for fine sediment redistribution within the channel system, but also for riparian vegetation dynamics, temperature and oxygen regimes, etc., all of which affect river habitat. In fact, it is the nature of streamflow variability, which includes flood episodes, that is fundamental for understanding long-term riverine landscape evolution.

The natural hydrological variability is expressed at different timescales. This is illustrated by a typical segment of daily streamflow observed at the outlet of an undisturbed mountainous basin in Southern Colorado (USA, Fig. 4). Interannual variability describes the change in streamflow properties (total volume, peak flow magnitude, etc.) between years. Within a year, one can easily identify a regular seasonal component in the hydrograph that is due to snowmelt in spring and early summer. Daily variability is caused by individual rainfall events. Large floods are most effective in reorganising the physical riverine environment. However, periods between floods, here called the recovery period, play an important role as well (see Fig. 4). It has been argued that in alluvial rivers the recovery period may in fact define the representative discharge to which channel shape is, on the average, adjusted (e.g., Wolman and Gerson, 1978; Kochel, 1988).

The range and nature of streamflow variability play a central role in the long-term geomorphological evolution of rivers; primarily because they control the redistribution of sediment, erosion and deposition. Studies have demonstrated that the spatial structure of a stream is related to the type of material that defines the dominant boundary resistance, to the sediment transporting capacity of flow, and to the time since the last dominant flood disturbance (e.g., Kochel, 1988; Pitlick, 1993; Rumsby and Macklin, 1994; Madej, 1999). Also important for the recovery of streams to their pre-flood state is the seasonality and intermittency of flow. In highly seasonal streams (such as the Tomichi Creek, Fig. 4) and intermittent or ephemeral streams, geomorphic work is concentrated in a short period, which generally leads to episodic behaviour with infrequent and large erosion periods, followed by long recovery times in which gradual channel aggradation dominates (e.g., Wolman and Gerson, 1978; Nanson, 1986; Molnar, 2001; Sloan et al., 2001).

The natural sequence of disturbances and recovery periods means that the riverine landscape is in a state of constant adjustment (e.g., Petts et al., 1995). The range of geomorphic adjustment is determined by the scale and nature of the disturbances, the two end-members being frequent low-magnitude floods (ecologically not always disturbance events) which are a predictable part of the natural hydrological regime, and infrequent and unpredictable large floods.

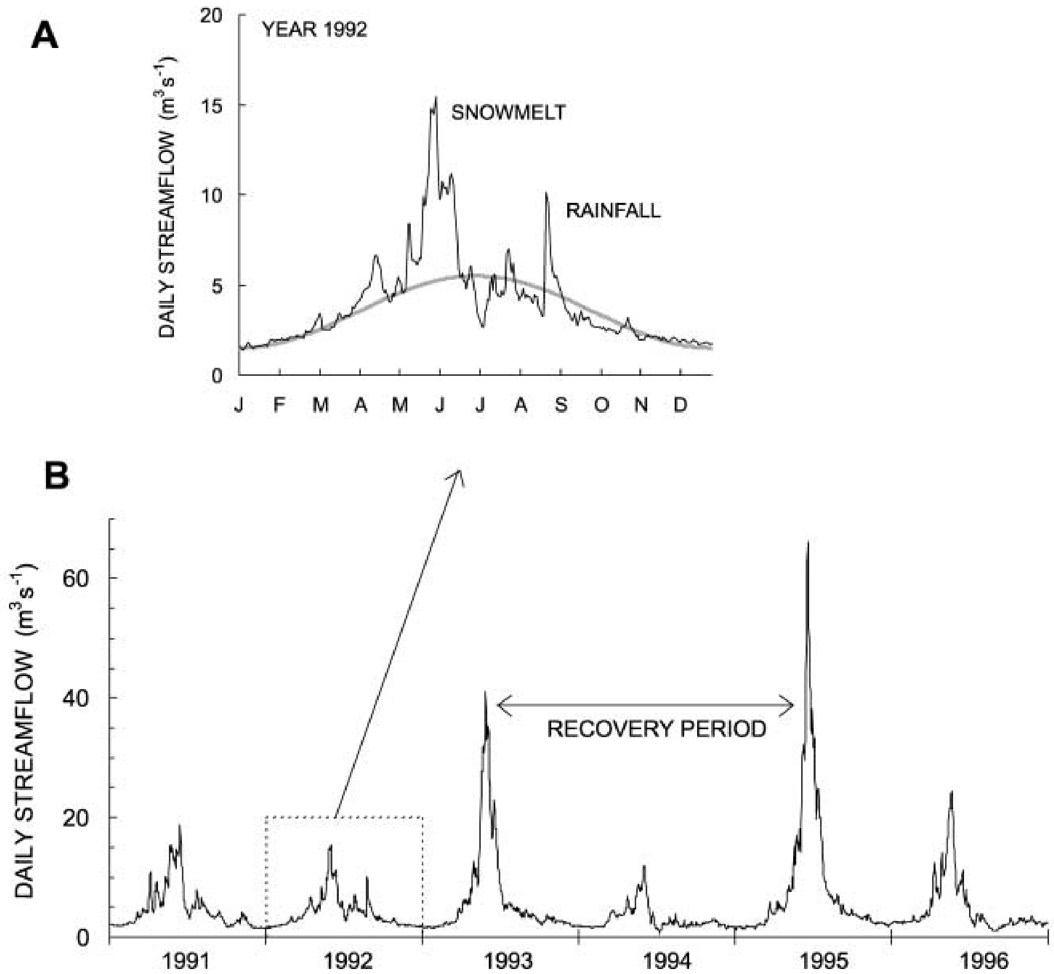

Figure 4. Daily streamflow of Tomichi Creek measured at Gunnison, Colorado, USA, for the period 1991–1996. The basin drains an area of 2748 km^2 in the Southern Rocky Mountains; gauging station is at 2325 m a.s.l. (A) Seasonal component of the hydrological regime (gray line) with snowmelt and rainfall floods in 1992 depicted. (B) Interannual variability and the notion of the recovery period between floods.

Changes in the hydrological regime

It has been argued that the natural hydrological regime plays a critical role in sustaining native biodiversity and ecosystem integrity in catchments (e.g., Poff et al., 1997). The climatic environment exerts a strong control on the natural hydrological regime. In semiarid and arid environments floods have the potential to cause greater landform change because of generally more erodible soils, less vegetation cover and flashy character of floods. Although rainfall maxima are generally lower in arid regions than in temperate regions, runoff maxima can be much higher (Osterkamp and Friedman, 2000). Channel erosion rates are also generally higher than in perennial streams (e.g., Hooke and Mant, 2000). In fact, semiarid and arid environments are likely to be very sensitive to even slight variation in the intensity of precipitation and runoff (e.g., Grimm et al., 1997; Molnar and Ramirez, 2001).

It is important to understand changes in the hydrological regime which may have far-reaching ecological consequences (e.g., Richter et al., 1996; Poff, 1996; Poff et al., 1997; Richter and Richter, 2000). Three broad categories of changes can be identified: anthropogenic catchment-related activities, natural climate variability, and potential climate change.

The main *anthropogenic* alterations of the hydrological regime come from activities in the catchment such as deforestation, grazing, landuse changes, or direct interference with the flow regime by water and sediment extraction, river engineering, floodplain destruction, dam construction. Changes in landuse strongly affect riverine landscapes by promoting upland erosion and sediment delivery to the streams, and by increasing flood peaks and channel erosion (e.g., Haigh et al. 1990; Brooks and Brierley, 1997; Van Steeter and Pitlick, 1998; White and Garcia-Ruiz, 1998; Prosser et al., 2001). Dam construction (for hydropower production purposes, flood retention, etc.) can dramatically change the hydrological regime, in particular the magnitude of flood peaks and their timing, as well as the sediment regime downstream of the dam. The case of Glen Canyon Dam in Utah, USA, for example, illustrates how the removal of the regular annual snowmelt flood and the decreased sediment supply adversely affected the riverine landscape in Grand Canyon downstream of the dam by eroding sand bars and promoting the invasion of non-native species adapted to colder, clearer water and less variable flow (Andrews and Pizzi, 2000; Topping et al., 2000).

Natural variability in large scale atmospheric circulation patterns affects the magnitude and distribution of extreme hydroclimatic events. Short-term changes in atmospheric circulation, such as those connected with the warm and cold phases of the Southern Oscillation phenomenon were shown to affect the hydroclimate across the world (e.g., Barnett et al., 1988; Piechota and Dracup 1996). In addition to high frequency variability present in hydroclimate data, recent studies have shown significant and persistent long-term trends in precipitation and streamflow (e.g., Karl and Knight, 1998; Lins and Slack, 1999). This low frequency variability in regional climate has been related to large scale pressure and temperature anomalies in the Pacific and Atlantic Oceans (e.g., Mantua et al., 1997; Zhang et al., 1997; Cayan et al., 1998). The global causes of such decadal-scale climate anomalies are being studied as an avenue for better predictability of extreme hydrological events in the future (e.g., Latif and Barnett, 1994; Rumsby and Macklin, 1994).

In addition to natural variability in climate, the issue of persistent *climate change* has recently received considerable attention. In particular it has been argued that the increase in greenhouse gasses and the resulting global warming of the atmosphere may lead to both global and local changes in weather. An increased occurrence of heavy rains and floods is predicted in some regions of the world (e.g., Fowler and Hennessy, 1995). The climate change issue has led to numerous studies of the effects on water resources. For example, using climate change scenarios of a gradual increase in greenhouse gasses and sulphate aerosols for the Arno River Basin (Italy), Burlando and Rosso (2002a) demonstrate a shift of local storm patterns towards shorter and more intense summer convective rainfall. Numerous other investigations emphasise major impacts of climate change on the hydrological regime at the catchment scale and on the generation of extreme floods (e.g., Knox, 1993; Galimberti-Aghion and Burlando, 1999; Burlando and Rosso, 2002b).

Modelling catchment and channel processes

An integrated catchment assessment scheme consists in principle of a modelling system which combines hydrological, hydrodynamic, sediment and ecosystem models. Individual elements of this modelling system have been well established in the scientific community. However, the successful integration into a catchment framework, which simulates water, sediment and ecosystem dynamics in the riverine landscape on a continuous basis in time and distributed in space is still in its infancy. In this section, we discuss some tasks, problems and challenges involved in setting up an integrated catchment model. The four foundations of such a catchment model are schematised in Figure 5. The riverine landscape, where streamflow routing, sediment transport and ecosystem evaluation models converge, is at the centre of this modelling system.

General modelling approach

The *hydrological* foundation is a physically-based distributed rainfall-runoff model which estimates the spatially and temporally variable runoff production $q_w(s,t)$ in the catchment driven by interactions between climate, soil, vegetation and surface topography. This model should include all relevant processes of the hydrological cycle at the land surface (evaporation, interception, snowmelt, etc.), in the unsaturated soil zone (infiltration, transpiration, etc.), and in the groundwater compartment (percolation, recharge, etc.). Numerous models of this type exist, and are characterised by various levels of complexity. Perhaps the best known are models developed around the blueprint provided by the European

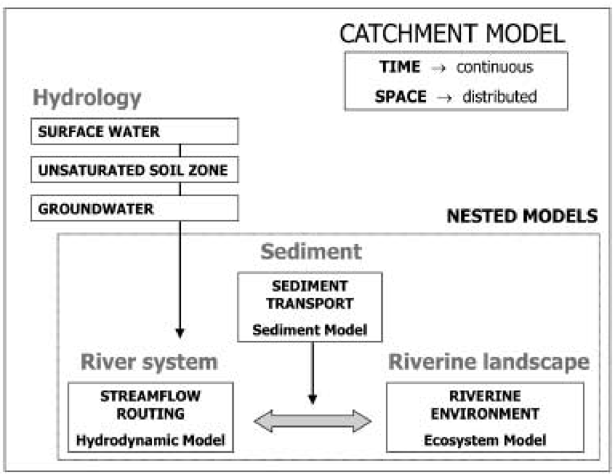

Figure 5. Schematic view of an integrated catchment model. Model components (river system hydraulics, sediment transport, riverine ecosystems) addressing local scales are nested into processes at larger scales (hydrological model).

Hydrological System (SHE) concept (e.g. Abbott et al., 1986a; 1986b; for other examples see Singh, 1995). Distributed hydrological modelling relies strongly on the availability of accurate geo-spatial data (elevation, soils, landuse, vegetation, etc.) and hydroclimatic data, in particular spatially distributed precipitation (e.g., Ogden et al., 2001).

The *river network* foundation is a hydrodynamic streamflow routing model built on principles of conservation of mass and momentum of flowing water (the so-called St. Venant system of equations) which transfers the runoff produced in the catchment through the stream system. The system of governing equations can be solved in one (e.g., applications at the river network scale) or more dimensions (e.g., river reach applications), and can be simplified based on the transient nature of flow (e.g., the choice between dynamic, diffusion or kinematic wave approximations). Streamflow routing is not only important for determining the transfer of water in space and time through the river network, but also for estimating the continuous distribution of hydraulic properties of flow, such as flow depth, vectors of velocity and bed shear stress (e.g., Lane and Richards, 1998; Crowder and Diplas, 2000).

The *sedimentological* foundation is a sediment transport model which estimates the spatially and temporally variable fluxes of sediment $q_s(s,t)$ in the catchment driven by runoff and diffusion processes, and limited by the erodibility of the land surface. The hillslopes are a source of fine sediment, which is eroded by shallow overland flow (sheet, rill and gully erosion) and delivered to the drainage network. Channelised surface runoff has a higher sediment transport capacity, which results in the motion of coarse sediment particles either delivered from upstream areas or eroded from the river bed. The imbalance between sediment supply, erodibility of the channel boundary, and the sediment transporting capacity of flow, determine whether erosion or deposition will occur in a river reach. Models of channel change in mobile bed streams are based on the evaluation of this sediment imbalance (e.g., Wiele et al.,1996; 1999).

The *riverine landscape* foundation is built on models of ecosystem dynamics in the riverine environment. Methodologies and models for assessing river habitat quality, such as instream flow assessment techniques, rely on relations between instream habitat and properties of flow and sediment (e.g., Milhous et al., 1989; Petts et al., 1995). Studies have shown that the spatial distribution of habitat and the complex spatial pattern of flow hydraulics and stream bed properties are strongly linked (e.g., Leclerc et al., 1995; 1996; Ghanem et al., 1996; Crowder and Diplas, 2000). Current habitat models build on these relationships, and map hydraulic habitat suitability in the river environment (e.g., Jorde, 1996; Schneider et al., 2001).

Although not considered as a separate foundation, water quality is an important element of the integrated catchment assessment scheme. As such it is contained in all of the above models, for instance, in the evaluation of pollutant production and transfer through the catchment and river system, and in the role water chemistry and temperature play in river habitat on the reach scale (e.g., Tockner et al., 2000).

Problems of scale

Perhaps the main obstacle to a successful integration of hydrological and ecological modelling studies in the context of riverine landscapes lies in the different scales of interest within the hydrological and ecological scientific communities.

Spatial scale. Habitat modelling studies have generally concentrated on a river reach scale. At this scale, sediment transport, erosion and deposition are often considered not important, and are, therefore, neglected. The focus in habitat modelling has generally been on the parameterisation of surface roughness since it plays a crucial role in the prediction of the flow pattern and the resulting habitat conditions (e.g., Lane, 1998; Lane and Richards, 1998; Hardy, 1998; Crowder and Diplas, 2000). On the other hand, hydrological analyses of channel change have generally concentrated on a larger, river network scale. Sediment transport, erosion and deposition in the channel system are not negligible at this scale. However, the models used to simulate average channel degradation and aggradation (for instance for flood protection purposes or to determine erosion downstream of dams) are generally one-dimensional, and are thus of little use for the detailed study of river habitat (e.g., Dawdy and Vanoni, 1986; Holly and Karim, 1986). More detailed hydrodynamic models have also been used for modelling sediment erosion and deposition in the channel, the floodplain and recirculation zones (e.g., Nicholas and Walling, 1998; Wiele et al. 1996; 1999). The latter models may be useful for river habitat studies but cannot at present be applied easily in long-term simulation.

Temporal Scale. The catchment assessment and modelling framework discussed here has long-term behaviour and modelling as its goal. It is in long-term simulation that feedbacks between hydrological and ecological processes can be included, and, hopefully, where major advancements in the future will be made. In geomorphology, first steps in this direction were made by so-called landscape evolution models, which have been applied to study the possible effects of climate change (for instance rainfall intensity) on long-term sediment yield and landscape change (e.g., Howard, 1994; Tucker and Slingerland, 1997; Coulthard et al., 2000). However, a detailed focus on the fluvial landscape is still lacking. We expect that such simulation studies (both with deterministic and stochastic components) will be a useful tool for studying the future effects of climate and catchment change on riverine landscapes.

The concept of nested modelling offers a way to face the problem of scale. This approach would allow fine resolution models (both in the time and the space domains) to be "nested" into models operating at larger scales, which dictate the boundary and initial conditions of the detailed models. The performance of individual models and their related catchment assessment tools depends on the degree of conceptualisation of the physical processes, the parameterisation of the catchment surface and subsurface, the time and space discretisation, and many other interrelated factors, such as the presence of feedback mechanisms. The performance of the system as a whole contains a large degree of uncertainty and will require extensive calibration and verification using both point and spatial data (e.g., Beven and Binley, 1992; Beven, 1997; Refsgaard, 1997; Beven, 2001; 2002).

Catchment monitoring, i.e., the collection of temporal and spatial data of relevant hydrological and ecological processes, is crucial within the integrated catchment assessment framework. Catchment monitoring is complicated by the fact that the relevant processes operate at different temporal and spatial scales. This requires that a nested approach be adopted as well, and that catchment data are collected at micro to macro scales by means of ground-based as well as remote sensing methods. The joint problem of catchment monitoring and model development will continue to be fundamental in the future and will require a combined effort of hydrologists and ecologists.

Conclusions

The consideration of different temporal and spatial scales of adjustment is necessary for a complete understanding of the physical and biological environments of the riverine landscape. Set in a catchment framework and concentrating on changes in the physical environment, we evaluated the role of the hydrological regime and discussed the different elements that constitute an integrated catchment model, which can simulate the coupled interactions between flow regime and riverine ecosystem dynamics.

The onset of changes in the physical environment of the riverine landscape is often dictated by catchment response to climate and anthropogenic influences. To evaluate such influences, it is necessary to focus on the entire catchment rather than on the river system only. In this way, the continuity of fluxes of matter and energy in the catchment is maintained, the evaluation of the river environment at a site is connected with upstream catchment processes, and a memory of past changes in the hydrological and sedimentological regime is included.

In terms of modelling the long-term dynamics of riverine ecosystems, we suggest the catchment as a basis for evaluating the spatially distributed fluxes of water and sediment (summarised by Figs. 1 and 5). Detailed hydrological, hydrodynamic, sedimentological and ecosystem models for evaluating river habitat in stream reaches may be nested within the catchment framework. Joint efforts in identifying, describing and enumerating the feedbacks between precipitation, runoff, and the river environment on a catchment basis are feasible, and would benefit by including not only the hydrological extreme event-based scale but also the long-term dynamics perspective. Understanding the long-term dynamics may be helpful in providing a sound basis for aquatic ecosystem conservation policies and catchment rehabilitation projects (e.g., Lorenz et al., 1997). A recent step in this direction is the development of a scientific base for a comprehensive assessment of stream ecosystems in Switzerland (Bundi et al., 2000).

Individual models within the framework also need to be improved and their interactions need to be better understood. As catchment models become increasingly complex there are three special areas of concern (e.g., O'Connell and Todini, 1996). The first problem is parameter identifiability and estimation. It is necessary to avoid over-parameterisation, while maintaining the physically-based nature of the models. The second problem is uncertainty prediction. Uncertainty in model structure, parameters, and input variables translates into uncertainty in predictions in a nonlinear manner. It is crucial that this uncertainty is properly accounted for, for instance by ensemble predictions and by interpreting the results in a probabilistic framework. The third problem is model validation. If long-term modelling efforts, encompassing both hydrological and ecological objectives, are to be successful in the future, it is imperative that comprehensive catchment monitoring projects are implemented. A proper observation and data monitoring foundation is vital for the development and verification of a coupled catchment model.

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References

Abbott, M. B., J. C. Bathurst, J. A. Cunge, P. E. O'Connell and J. Rasmussen, 1986 a. An introduction to the European Hydrological system – Système Hydrologique Européen "SHE" 1: History and philosophy of a physically based distributed modelling system. J. Hydrol. **87:** 45–59.

Abbott, M. B., J. C. Bathurst, J. A. Cunge, P. E. O'Connell and J. Rasmussen, 1986 b. An introduction to the European Hydrological system – Système Hydrologique Européen "SHE" 2: Structure of a physically based distributed modelling system. J. Hydrol. **87:** 61–77.

Andrews, E. D. and L. A. Pizzi, 2000. Origin of the Colorado River experimental flood in Grand Canyon. Hydrol. Sci. J. **45:** 607–627.

Bain, M. B., J. T. Finn and H. E. Booke, 1988. Streamflow regulation and fish community structure. Ecology **69:** 382–392.

Baker, V. R., 1977. Stream channel response to floods, with examples from central Texas. Geol. Soc. Amer. Bull. **88:** 1057–1071.

Baker, V.R., 1994. Geomorphological understanding of floods. Geomorphology **10:** 139–156.

Barnett, T. P., L. Dumenil, U. Schlese and E. Roeckner, 1988. The effect of the Eurasian snow cover on global climate. Science **239:** 504–507.

Bendix, J. and C. R. Hupp, 2000. Hydrological and geomorphological impacts on riparian plant communities. Hydrol. Process. **14:** 2977–2990.

Beven, K. J., 1997. Distributed hydrological modelling: Applications of the TOPMODEL concept. Chichester and Wiley, 348 pp.

Beven, K. J., 2001. How far can we go in distributed hydrological modelling. Hydrol. Earth Syst. Sci. **5:** 1–12.

Beven, K. J., 2002. The future of distributed modelling. Hydrol. Process. **16:** 169–172.

Beven, K. J. and A. Binley, 1992. The future of distributed models: Model calibration and uncertainty prediction. Hydrol. Process. **6:** 279–298.

Brooks, A. P. and G. J. Brierley, 1997. Geomorphic response of lower Bega River to catchment disturbance, 1851 – 1926. Geomorphology **18:** 291–304.

Brooks, G. R. and D. E. Lawrence, 1999. The drainage of the Lake Ha!Ha! reservoir and downstream geomorphic impacts along Ha!Ha! River, Saguenay area, Quebec, Canada. Geomorphology **28:** 141–158.

Bull, W. B., 1988. Floods: Aggradation and degradation. In: V. R. Baker, R.C. Kochel and P. C. Patton (eds.), Flood Geomorphology, Wiley, New York, pp. 157–168.

Bundi, U., A. Peter, A. Frutiger, M. Hütte, P. Liechti and U. Sieber, 2000. Scientific base and modular concept for comprehensive assessment of streams in Switzerland. Hydrobiologia **422/423:** 477–487.

Burlando, P. and R. Rosso, 2002 a. Effects of transient climate change on basin hydrology, 1. Precipitation scenarios for the Arno River Basin, central Italy. Hydrol. Process. **16:** 1151–1175.

Burlando, P. and R. Rosso, 2002 b. Effects of transient climate change on basin hydrology, 2. Impacts on runoff variability of the Arno River Basin, central Italy. Hydrol. Process. **16:** 1177–1199.

Carling, P., 1995. Implications of sediment transport for instream flow modelling of aquatic habitat. In: D. M. Harper and A. J. D. Ferguson (eds.), The Ecological Basis for River Management, Wiley and Sons, Chichester, pp. 17–31.

Cayan, D. R., M. D. Dettinger, H. F. Diaz and N. E. Graham, 1998. Decadal variability of precipitation over Western North America. J. Climate **11:** 3148–3166.

Costa, J. E. and J. E. O'Connor, 1995. Geomorphologically effective floods. Geophysical Monograph **89**, AGU, 45–56.

Coulthard, T. J., M. J. Kirkby and M. G. Macklin, 2000. Modelling geomorphic response to environmental change in an upland catchment. Hydrol. Process. **14:** 2031–2045.

Crowder, D. W. and P. Diplas, 2000. Using two-dimensional hydrodynamic models at scales of ecological importance. J. Hydrol. **230:** 172–191.

Dawdy, D. R. and V. A. Vanoni, 1986. Modeling alluvial channels. Water Resour. Res. **22:** 71–81.

Edwards, W. M. and L. B. Owens, 1991. Large storm effects on total soil-erosion. J. Soil Water Cons. **46:** 75–78.

Fowler, A. M. and K. J. Hennessy, 1995. Potential impacts of global warming on the frequency and magnitude of heavy precipitation. Nat. Hazards **11:** 283–303.

Friedman, J. M., W. R. Osterkamp and W. M. Lewis, 1996. Channel narrowing and vegetation development following a Great-Plains flood. Ecology **77:** 2167–2181.

Galimberti-Aghion, C. and P. Burlando, 1999. Climate forcing and flood frequency. In: P. Clapps and F. Siccardi (eds.), Mediterranean Storms, pp. 311–339.

Ghanem, A. F., P. Steffler, F. Hicks and C. Katopodis, 1996. Two-dimensional hydraulic simulation of physical habitat conditions in flowing streams. Regul. Rivers **12:** 185–200.

Grimm, N. B., A. Chacon, C. N. Dahm, S. W. Hostetler, O. T. Lind, P. L. Starkweather and W. W. Wurtsbaugh, 1997. Sensitivity of aquatic ecosystems to climatic and anthropogenic changes: the Basin and Range, American Southwest and Mexico. Hydrol. Process. **11:** 1023–1041.

Gutierrez, F., M. Gutierrez and C. Sancho, 1998. Geomorphological and sedimentological analysis of a catastrophic flash flood in the Aras drainage basin (Central Pyrenees, Spain). Geomorphology **22:** 265–283.

Haigh, M. J., J. S. Rawat and H. S. Bisht, 1990. Hydrological impact of deforestation in the central Himalaya. IAHS Publ. No. **190**, 419–433.

Hardy, T. B., 1998. The future of habitat modeling and instream flow assessment techniques. Regul. Rivers **14:** 405–420.

Holly, F. M. and M. F. Karim, 1986. Simulation of Missouri River bed degradation. J. Hydraul. Eng. **112:** 497–517.

Hooke, J. M. and J. M. Mant, 2000. Geomorphological impacts of a flood event on ephemeral channels in SE Spain. Geomorphology **34:** 163–180.

House, P. K. and P. A. Pearthree, 1995. A geomorphologic and hydrologic evaluation of an extraordinary flood discharge estimate: Bronco Creek, Arizona. Water Resour. Res. **31:** 3059–3073.

Howard, A. D., 1994. A detachment-limited model of drainage basin evolution. Water Resour. Res. **30:** 2261–2285.

Jorde, K., 1996. Ökologisch begründete, dynamische Mindestwasserregelungen bei Ausleitungskraftwerken (German). PhD Dissertation, University of Stuttgart.

Junk, W. J., P. B. Bayley and R. E. Sparks, 1989. The flood pulse concept in river-floodplain systems. Can. Spec. Publ. Fish. Aquat. Sci. **106:** 110–127.

Kale, V. S., L. L. Ely, Y. Enzel and V. R. Baker, 1994. Geomorphic and hydrologic aspects of monsoon floods on the Narmada and Tapi Rivers in central India. Geomorphology **10:** 157–168.

Karl, T. R. and R. W. Knight, 1998. Secular trends of precipitation amount, frequency, and intensity in the United States. Bull. Amer. Met. Soc. **79:** 231–241.

Knox, J. C., 1993. Large increases in flood magnitude in response to modest changes in climate. Nature **361:** 430–432.

Kochel, C. G., 1988. Geomorphic impact of large floods: Review and new perspectives on magnitude and frequency. In: V. R. Baker, R. C. Kochel and P. C. Patton (eds.), Flood Geomorphology, Wiley and Sons, New York, pp. 169–187.

Lane, S. N., 1998. Hydraulic modeling in hydrology and geomorphology: A review of high resolution approaches. Hydrol. Process. **12:** 1131–1150.

Lane, S. N., K. S. Richards and J. H. Chandler, 1996. Discharge and sediment supply controls on erosion and deposition in a dynamic alluvial channel. Geomorphology **15:** 1–15.

Lane, S. N. and K. S. Richards, 1998. High resolution, two-dimensional spatial modelling of flow processes in a multithread channel. Hydrol. Process. **12:** 1279–1298.

Latif, M. and T. P. Barnett, 1994. Causes of decadal climate variability over the North Pacific and North America. Science **266:** 634–637.

Leclerc, M., A. Boudreault, J. A. Bechara and G. Corfa, 1995. 2-dimensional hydrodynamic modeling – a neglected tool in the instream flow incremental methodology. Trans. Amer. Fish. Soc. **124:** 645–662.

Leclerc, M., P. Boudreau, J. A. Bechara and L. Belzile, 1996. Numerical method for modelling spawning habitat dynamics of landlocked salmon, Salmo salar. Regul. Rivers **12:** 273–285.

Lins, H. F. and J. R. Slack, 1999. Streamflow trends in the United States. Geophys. Res. Let. **26:** 227–230.

Lorenz, C. M., G. M. Van Dijk, A. G. M. Van Hattum and W. P. Cofino, 1997. Concepts in river ecology: Implications for indicator development. Regul. Rivers **13:** 501–516.

Madej, M. A., 1999. Temporal and spatial variability in thalweg profiles of a gravel-bed river. Earth Surf. Process. Landforms **24:** 1153–1169.

Magilligan, F. J., 1992. Thresholds and the spatial variability of flood power during extreme floods. Geomorphology **5:** 373–390.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace and R. C. Francis, 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Amer. Met. Soc. **78:** 1069–1079.

Michaud, J. D., K. K. Hirschboeck and M. Winchell, 2001. Regional variations in small-basin floods in the United States. Water Resour. Res. **37:** 1405–1416.

Milhous, R. T., M. A. Updike and D. M. Schneider, 1989. Physical habitat simulation system (PHABSIM) reference manual, Version II. Instream flow information paper No. 26. US Fish and Wildlife Service Biological Report **89** (16).

Miller, A. J., 1995. Valley morphology and boundary conditions influencing spatial patterns of flood flow. Geophysical Monograph **89**, AGU, 57–81.

Minshal, G. W., 1988. Stream ecosystem theory: a global perspective. J. North Amer. Benth. Soc. **7:** 263–288.

Molnar, P., 2001. Precipitation and erosion dynamics in the Rio Puerco Basin. Ph.D. Dissertation, Colorado State University, Fort Collins, CO, 258 pp.

Molnar, P. and J. A. Ramirez, 2001. Recent trends in precipitation and streamflow in the Rio Puerco Basin. J. Climate **14:** 2317–2328.

Montgomery, D. R., 1999. Process domains and the river continuum. J. Amer. Water Resour. Assoc. **35:** 397–410.

Nanson, G. C., 1986. Episodes of vertical accreation and catastrophic stripping – A model of disequilibrium floodplain development. Geol. Soc. Amer. Bull. **97:** 1467–1475.

Nicholas, A. P. and D. E. Walling, 1998. Numerical modelling of floodplain hydraulics and suspended sediment transport and deposition. Hydrol. Process. **12:** 1339–1355.

O'Connell, P. E. and E. Todini, 1996. Modelling of rainfall, flow and mass transport in hydrological systems: an overview. J. Hydrol. **175:** 3–16.

Ogden, F. L., J. Garbrecht, P .A. DeBarry and L. E. Johnson, 2001. GIS and distributed catchment models. II: Modules, interfaces, and models. J. Hydrol. Eng. **6:** 515–523.

Osterkamp, W. R. and J. M. Friedman, 2000. The disparity between extreme rainfall events and rare floods – with emphasis on the semi-arid American West. Hydrol. Process. **14:** 2817–2829.

Petts, G., I. Maddock, M. Bickerton and A. J. D. Ferguson, 1995. Linking hydrology and ecology: The scientific basis for river management. In: D. M. Harper and A. J. D. Ferguson (eds.), The Ecological Basis for River Management, Wiley and Sons, Chichester, pp. 1–16.

Piechota, T. C. and J. A. Dracup, 1996. Drought and regional hydrologic variation in the United States: Associations with the El Niño-Southern Oscillation. Water Resour. Res. **32:** 1359–1373.

Pitlick, J., 1993. Response and recovery of a sub-alpine stream following a catastrophic flood. Geol. Soc. Amer. Bull. **105:** 657–670.

Poesen, J. W. A. and J. M. Hooke, 1997. Erosion, flooding and channel management in Mediterranean environments of southern Europe. Prog. Phys. Geogr. **21:** 157–199.

Poff, L. N., 1996. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. Freshwater Biology **36:** 71–91.

Poff, L. N. and J. V. Ward, 1989. Implications of streamflow variability and predictability for lotic community structure: A regional analysis of streamflow patterns. Can. J. Fish. Aquat. Sci. **46:** 1805–1817.

Poff, L. N. and J. D. Allan, 1995. Functional organisation of stream fish assemblages in relation to hydrological variability. Ecology **76:** 606–627.

Poff, L. N., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks and J. C. Stromberg, 1997. The natural flow regime: A paradigm for river conservation and restoration. BioScience **47:** 769–784.

Prosser, I. P., I. D. Rutherfurd, J. M. Olley, W. J. Young, P. J. Wallbrink and C. J. Moran, 2001. Large-scale patterns of erosion and sediment transport in river networks, with examples from Australia. Marine and Freshwater Res. **52:** 81–99.

Refsgaard, J. C., 1997. Parameterisation, calibration and validation of distributed hydrological models. J. Hydrol. **198:** 69–97.

Resh, V. H., A. V. Brown, A. P. Coovich, M. E. Gurtz, H. W. Li, G. W. Minshal, S. R. Reice, A. L. Sheldon, J.B. Wallace and R. Wissmar, 1988. The role of disturbance in stream ecology. J. North Amer. Benth. Soc. **7:** 433–455.

Richter, B. D., J. Y. Baumgartner, J. Powell and D. P. Braun, 1996. A method for assessing hydrologic alteration within ecosystems. Conserv. Biology **10:** 1163–1174.

Richter, B. D. and H. E. Richter, 2000. Prescribing flood regimes to sustain riparian ecosystems along meandering rivers. Conserv. Biology **14:** 1467–1478.

Rosso, R. and L. Serva, 1998. 19 Giugno 1996: Alluvione in Versilia e Garfagnana (Italian). ANPA-ARPAT, 315 pp.

Rumsby, B. T. and M. G. Macklin, 1994. Channel and floodplain responses to recent abrupt climate change: The Tyne Basin, Northern England. Earth Surf. Process. Landforms **19:** 499–515.

Schneider, M., J. Giesecke and F. Zöllner, 2001. CASIMIR: Hilfsmittel zur Mindestwasserfestlegung unter Berücksichtigung von Ökologie und Ökonomie (German). Wasserwirtschaft 91: 486–490

Schumm, S. A., 1973. Geomorphic thresholds and complex response of drainage systems. In: M. Morisawa (ed.), Fluvial Geomorphology, 299–310.

Singh, V. P., 1995. Computer Models of Catchment Hydrology. Water Resources Publications, Colorado, 1130 pp.

Sloan, J., J. R. Miller and N. Lancaster, 2001. Response and recovery of the Eel River, California, and its tributaries to floods in 1955, 1964, and 1997. Geomorphology **36:** 129–154.

Strahler, A. N., 1957. Quantitative analysis of catchment geomorphology. Transactions of the American Geophysical Union 38: 913–920.

Tockner, K., F. Malard and J. V. Ward, 2000. An extension of the flood pulse concept. Hydrol. Process. **14:** 2861–2883.

Topping, D. J., D. M. Rubin and L. E. Vierra, 2000. Colorado River sediment transport: 1. Natural sediment supply limitation and the influence of Glen Canyon Dam. Water Resour. Res. **36:** 515–542.

Tucker, G. E. and R. Slingerland, 1997. Drainage responses to climate change. Water Resour. Res. **33:** 2031–2047.

Van Steeter, M. M. and J. Pitlick, 1998. Geomorphology and endangered fish habitats of the upper Colorado River: 1. Historic changes in streamflow, sediment load, and channel morphology. Water Resour. Res. **34:** 287–302.
Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell and C.E. Cushing, 1980. The river continuum concept, Can. Spec. Publ. Fish. Aquat. Sci. **37:** 130–137.
White, S. and J. M. Garcia-Ruiz, 1998. Extreme erosional events and their role in mountain areas of Northern Spain. Ambio **27:** 300–305.
Wiele, S. M., J. B. Graf and J. D. Smith, 1996. Sand deposition in the Colorado River in the Grand Canyon from flooding of the Little Colorado River. Water Resour. Res. **32:** 3579–3596.
Wiele, S. M., E. D. Andrews and E. R. Griffin, 1999. The effect of sand concentration on depositional rate, magnitude, and location in the Colorado River below the Little Colorado River. Geophysical Monograph **110**, AGU.
Wohl, E., 2000. Mountain rivers. Water Resources Monograph **14**, AGU, 320 pp.
Wolman, M. G. and R. Gerson, 1978. Relative scales of time and effectiveness of climate in catchment hydrology. Earth Surf. Process. **3:** 189-203.
Wolman, M. G. and J. P. Miller, 1960. Magnitude and frequency of forces in geomorphic processes. J. Geology **68:** 54–74.
Zhang, Y., J. M. Wallace and D. S. Battisti, 1997. ENSO-like interdecadal variability: 1900-93. J. Climate **10:** 1004–1020.