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Surface Water–Groundwater Exchange Processes and Fluvial Ecosystem Function: An Analysis of Temporal and Spatial Scale Dependency

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6.1 Introduction

There is general agreement that river flow variability is a major driving force in shaping fluvial hydrosystems and in determining ecological strategies and species richness in water courses (Southwood, 1977; Hildrew and Townsend, 1987; Townsend, 1989; Poff, 1997). Flow variability creates conditions for water fluxes and linked material exchanges between surface and groundwater (SGW), resulting in an active interface zone with varying boundaries in time and space. This interface or ecotone is termed the hyporheic zone, where flow direction and strength of changes over time and space varies, providing dynamic conditions for metabolic and biogeochemical processes. Hydrologic and geomorphic contexts (including SWG exchange) establish a template upon which biotic processes operate (Poff, 1997). Thus, effectively to address natural trends as well as human-modified changes in fluvial ecosystems, ecological and hydrologic perspectives must be merged. For management, the priority is to identify the timing, frequency, magnitude, and duration in flow variability that is needed to maintain processes as near to natural conditions in space and time as possible (Petts *et al.*, 2005). Hence, information

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on flow variability is key to judging ecosystem resilience in response to natural or human-induced dynamic change (Connel and Wayne, 1983; Bunn *et al.*, 2006; Thoms, 2006).

The objective of this chapter is to explore how flow variability affects SGW interactions and thereby functions of the fluvial ecosystem along the 'hyporheic corridor' from head waters to river mouth (Stanford and Ward, 1993). The chapter begins by defining fluvial ecosystems in terms of two aspects of their structure and function – biogeochemical processes and biotic structure – that are expected to respond to flow variability and SGW exchange. Data from a field experiment serve to illustrate dimensions and variability of SGW exchange at one location in space and time. The range of space and time scales over which SGW interactions occur is then considered in a case study. This analysis takes the form of a cross-continental comparison of river basins in humid (Europe) and arid/semi-arid (southwestern USA) settings, generalizing the dynamics of SGW exchange in contrasting environments as recommended by Poff *et al.* (2006). Finally, the relationship between patterns of flow variability and biotic processes is explored, considering important biological and anthropogenic influences on SGW exchange at different spatio-temporal scales within fluvial ecosystems.

6.2 Fluvial Ecosystems: The Hydrogeomorphic Template and Ecosystem Function

Fluvial ecosystems are defined herein as comprising the annually flooded channel (i.e., surface water, adjacent parafluvial zone with saturated sediment deposits, and underlying hyporheic zone) plus the laterally connected riparian zone. The hydrogeomorphic template is defined as the geomorphic and hydrologic features of the fluvial ecosystem – and their spatial and temporal variability – that control the intensity and direction of water movement, and thus establish conditions experienced by biotic communities. Vertical, lateral and longitudinal dimensions of the river–riparian–upland ecotone are expected to vary from headwaters to river mouth in predictable ways (Gregory *et al.*, 1991; Grimm and Fisher, 1992; Stanford and Ward, 1993; Dahm *et al.*, 1998). Depending upon location along the water course, connectivity between the river and its landscape should be enhanced or limited, shaping the limits and fluctuations of the hyporheic system. Heterogeneity in the fluvial ecosystem, including paleochannels in riverbed sediments or riparian floodplains, creates preferential flows. The magnitude and direction of these flows influences nutrient transport and biotic activity in the hyporheic environment, creating hot spots of biodiversity and production (Stanford and Gonser, 1998; McClain *et al.*, 2003).

6.2.1 Fluvial Ecosystem Function: Biogeochemical Dynamics

Biogeochemical dynamics in fluvial ecosystems can be described by conceptual models that recognize the opposing processes of hydrologic transport and retention, for example nutrient spiralling (Elwood *et al.*, 1983; Mulholland *et al.*, 1990). Nutrient spiralling and nutrient transformations that contribute to whole-ecosystem nutrient retention are influenced by flow variability and SGW interactions through: (i) effects on biota that are

responsible for nutrient processing; (ii) development of microhabitat conditions, such as redox conditions, that favour certain processes over others, and (iii) delivery of essential materials (macronutrients, organic carbon) from uplands to fluvial ecosystems or among different compartments of fluvial ecosystems. Finally, the biogeochemistry of fluvial ecosystems is a function of the biogeochemical processing in each component subsystem, linked by the fluxes of water among them (Fisher *et al.*, 1998).

Effects of SGW interactions on biogeochemical dynamics will vary depending on basin size. Small streams are subject to short-duration but severe floods. Fluxes from the bank to the clearly delimited riverbed are direct, with consequent extensive interactions between soil and water. The contributions of material and water fluxes are usually unidirectional (basin to river). Small streams in their valleys are best visualized as the visible fraction of underground flows (Winter, 2001), rather than as disconnected gutters draining catchments. By contrast, large floodplain rivers have low bank length:volume ratios, and the river both deposits and entrains sediments and nutrients from parafluvial zones during floods. Major alluvial aquifers and extended floodplains are important storage reservoirs for water and nutrients that are mobilized during periodic floods. The contributions of groundwater from uplands are proportionately lower than for small streams, with a vast hyporheic zone interacting with the river and creating a fluvial 'riparian corridor' or 'hyporheic corridor' (e.g., Stanford and Ward, 1988, 1993). Thus, the magnitude and direction of connections between the catchment and its river vary downstream. Intermediate-sized rivers exhibit riffle–pool morphology featuring downwelling zones, where surface water enters the subsurface, alternating with upwelling zones, where hyporheic water is discharged to the surface. Matter fluxes are lateral (bidirectional exchanges with parafluvial and riparian groundwater) and vertical (bidirectional exchanges with the hyporheic zone). These patterns of SGW exchange strongly influence river biogeochemistry because of differential processing of nutrients and organic matter in surface and subsurface environments (e.g., Dent *et al.*, 2001), and because groundwater inputs often are chemically distinct from the river.

6.2.2 Fluvial Ecosystem Structure: Biotic Communities

Superimposed upon the hydrogeomorphic template of fluvial ecosystems are its habitats, which determine the structure and dynamics of biotic communities and their component populations. Extensive research and theory connects this template (especially flow dynamics) to communities of fish and macroinvertebrates (e.g., Southwood, 1977; Connell, 1978; Townsend, 1989). More recently, the importance of SGW exchanges and the different zones or 'biotopes' they create has been recognized (e.g., Boulton *et al.*, 1992; Lafont *et al.*, 2006). In sandy-bed rivers, surface benthos is often absent owing to scour, whereas deep hyporheos is protected from export and may thrive due to high rates of SGW exchange, which delivers organic material through the sandy matrix (Boulton, 1993; Rouch *et al.*, 1997; Fellows *et al.*, 2001). Of course, biotic communities include organisms within functional groups ranging from denitrifiers and nitrifiers (bacteria) to active predators that transform large biotic particles to small particles and dissolved nutrients (fish), and so these communities are essential components of biogeochemical dynamics.

6.3 Flow Variability and SGW Water Movements

Water flow drives nutrient fluxes in fluvial ecosystems. Flow variability induces fluctuations in water depth of river channel cross-sections (laterally) and along the long profile (downstream). Just as variation in surface water hydraulic gradient (a measure of the difference in water total energy between two points in space) drives water movement between points on a river, water movement between free-flowing water and connected unconfined porous media can be approximated using the hydraulic gradient (HG; see Chapter 9). Local conditions can create or enhance HG along a water course, generating local flow-paths in riverbed sediments and banks at angles from the main flow direction. The extent of SGW exchange will depend upon both HG and saturated hydraulic conductivity, according to Darcy's Law (e.g., Maidment, 1993). Variations in HG and hydraulic conductivity in space and time yield variations in water flow and SGW exchanges. Hydraulic conductivity values of the channel-lining layer range from 10^{-7} to $10^{3}\,m\,sec^{-1}$ (Calver, 2001). As a general rule, hydraulic conductivity of riverbed substrates is greater than that of bank sediments by a factor of 100 to 1000, such that water flux will be greater in bed sediments than in the banks at any given HG (e.g., Wroblicky *et al.*, 1998).

6.3.1 In Space

SGW exchange can occur in several directions. At small scales, exchange between surface and hyporheic waters is dictated by variation in form of the bed (Savant *et al.*, 1987; Thibodeaux and Boyle, 1987; Harvey and Bencala, 1993) or the influence of structural features – including biotic features such as macrophyte beds or fish nests (e.g., White, 1990; Dent *et al.*, 2000). These features cause local variation in vertical HG (VHG) or hydraulic conductivity, and hence SWG exchange. Heads of riffles are infiltration zones (downwelling) of surface water in the hyporheic zone, and discharge zones (upwelling) occur at the end of hyporheic flow paths, often at the tails of riffles. Similar variations occur at larger scales, such as variation in VHG near riffle-pool transitions (e.g., Dent *et al.*, 2001) and variation in hydraulic conductivity associated with abandoned channels in oxbows of meandering rivers. Such lateral water movements may also be linked to an existing HG between a river and shallow groundwater in the adjacent floodplain. Along the river corridor, hydraulic conductivity tends to decrease from headwaters, with their coarse sediments, to lowlands, where fine sediments dominate. This generalization is expressed in the hyporheic corridor concept (Stanford and Ward, 1993) as an increase in the ratio of annual overland flows to interstitial flows on floodplains from headwaters to river mouth.

Longitudinal components of SGW fluxes correspond to shortcuts in meanders, again as a result of HG and bank hydraulic conductivity. In general, bottom gradients are naturally steeper upstream within a river network, with more riffle-pool sequences per km and more pronounced steps, creating greater opportunity for SGW exchanges regardless of river flow regime. This idea was investigated using a three-dimensional mechanistic hydraulic model under steady-flow conditions (Cardenas *et al.*, 2004), parameterized with field hydraulic conductivity data for a channel bend. Heterogeneity of hydraulic conductivity, bed-form profile, and channel curvature had significant influences on hyporheic zone geometry, SGW flux magnitude, and residence time. The major cause of SGW

exchange was found to be the spatial density and magnitude of change in water-surface topography. Although these results are revealing, the steady-flow condition is a restricted case. In a natural river flow regime, a succession of transient HG occurs and particular combinations of HG duration and magnitude shape the three-dimensional boundaries of SGW exchange. To investigate this fuller suite of conditions, results from a field experiment are presented (Ruysschaert and Breil, 2004). Figures 6.1 and 6.2 illustrate how the

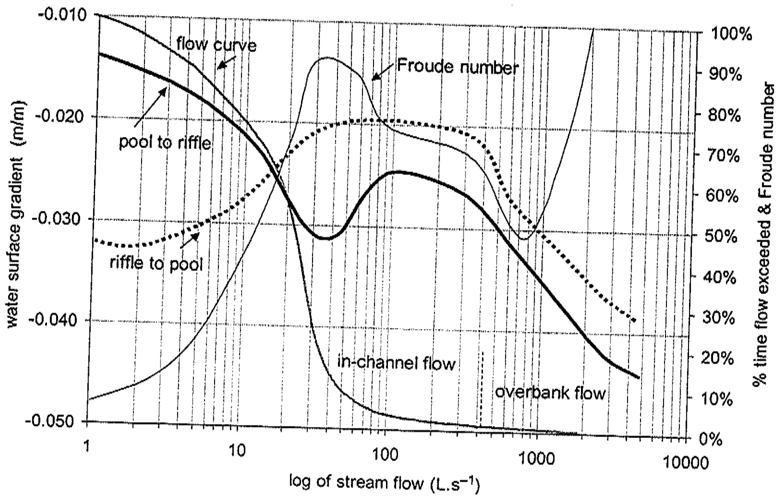

Figure 6.1 *Observed mean water surface gradients as a function of flow rate in a sequence of pool–riffle and riffle–pool geomorphic units for a small stream near Lyon, France (curves were manually smoothed from empirical data.)*

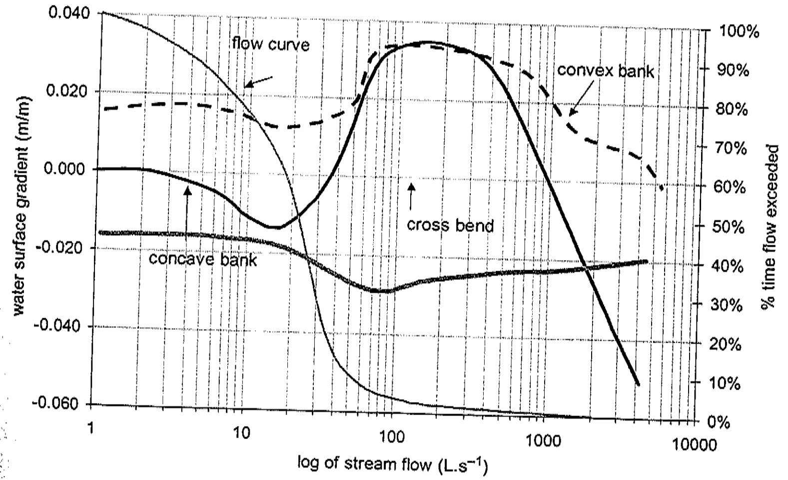

Figure 6.2 *Observed mean water-surface gradients as a function of flow rate in lateral direction between channel and convex and concave banks and longitudinal direction crossing a meander (cross bend) for a small stream near Lyon, France*

combined effect of vertical and planar geomorphic features – pool-riffle sequences and associated meanders – can influence the local free surface-water gradient at varying discharge. Local variations of these gradients create conditions for streambed VHG to change. Gradient–discharge curves are based upon mean observed values for hourly discharge class intervals over a period of 1 year, when discharge varied from no flow to a large flood. Negative gradient values indicate potential water movement from the free surface water in a lateral or downstream direction.

Surface-water hydraulic gradient in the pool–riffle sequence decreased with flow rate, exhibiting a minimum for an extended range of flows from 50 to 400 ls^{-1} (Figure 6.1). At discharge values above this threshold, only overbank flows can lead to larger gradients.

The pool-to-riffle gradient curve exhibited a more complex pattern, with an in-channel maximum for intermediate discharge. Comparison of gradient values indicated that the water surface becomes steeper in the pool–riffle sequence than in the riffle–pool at intermediate flows. A maximum hydraulic gradient at intermediate discharge makes sense when compared to the corresponding Froude hydraulic number (e.g., Maidment, 1993), which also exhibits a maximum (left scale in Figure 6.1) for the same flow range. The Froude number expresses the combined effect of stream channel roughness and overall bend curvature (which slow down water velocity) plus the driving gravitational force that results from stream gradients. The pool-riffle sequence locally increases channel roughness, inducing steeper HG. The opposite patterns of HG magnitude–discharge curves for the pool-riffle and riffle-pool units indicate local and temporarily unbalanced SGW exchange.

Lateral bank flows in both convex and concave directions are similar to the combined pattern of the pool-riffle and riffle-pool curves (Figure 6.2), showing that pool–riffle–pool sequence influence lateral SGW exchanges in a similar way. Only the longitudinal bank or cross bend flow seems insensitive to this effect but the gradient remains high regardless of flow rate, increasing slightly at intermediate flows. Bank gradient in the convex bank always flows toward the river (positive gradient) with an increase for larger flows. This pattern was not expected but it was confirmed with other measures. It reveals a persistent cross-bend flow near the channel. In the concave bank, the water surface gradient indicates flow from bank to river for a low-to-intermediate stream flow range and from river to the bank for larger stream flows.

Considering water surface gradient, corresponding flow rates and some range of values for hydraulic conductivity in the stream bed sediments and banks, it is possible roughly to compare rates of exchange between the longitudinal, lateral and vertical components. Results indicate that lateral flow in the convex bank and vertical flows in the pool–riffle and riffle–pool sequences account for almost 30% each of the yearly water exchange, but longitudinal bank and lateral concave bank flows account for only 10%. This specific case study example is not intended as a generalization but rather as an illustration of how complexity of fluvial geomorphology can produce spatially heterogeneous SGW exchanges. For larger water courses, the effect of bottom gradient should be less important than hydraulic conductivity of the flood plain (especially preferential flow-paths and paleochannels) in determining SGW exchange rates (Stanford and Ward, 1993).

6.3.2 In Time

Fluxes across the SGW interface are known to vary seasonally (e.g. Evans and Petts, 1997; Malcolm *et al.*, 2004). Based upon the case study presented above, larger HGs support downwelling in the channel at medium to high flows. These flow conditions occur ~60% of the year for this case study, compared with just 10% of the time (at low flow) when upwelling dominates. Three-dimensional SGW exchanges can persist with low, almost steady, flows except for the lateral concave bank. Gradient magnitude is emphasized with intermediate flows, which corresponds to unsteady flow conditions. Of course, these results may not apply in other contexts, such as streams or rivers that are strongly groundwater fed, where near-channel head gradients should be modified. During drier periods in more humid climates, groundwater feeds the river as baseflow. During wet weather, alternating rise and fall of river stage generates exchange fluxes from surface water to hyporheic and floodplain waters, and the reverse also occurs (Evans and Petts, 1997). In arid regions, VHG strengthens during the dry season, and the direction of SGW exchange may even shift from discharge to recharge (Stanley and Boulton, 1995). In human-controlled, steady low-flow conditions, vertical flow should predominate as a result of reduction in lateral head gradient between SW and shallow GW surface, but as shown in Figure 6.2, lateral and longitudinal flux can persist in river banks as a result of planar and vertical geomorphic features. Flow variations in time can modify SGW boundaries, producing greater changes than expected given the geomorphic template (Figures 6.1 and 6.2). Rapid change in flow emphasizes vertical hydraulic gradients between the channel and surrounding shallow floodplain groundwater, reinforcing lateral exchange rates. The latter case was shown to occur in a matter of hours during flooding of a mid-sized river in Arizona, USA (Marti *et al.*, 2000). The temporal distribution of flow variations and antecedent events are critical variables in determining SGW exchange boundaries, because VHG and even hydraulic conductivity can change rapidly. Thus, the total annual flux across the SGW interface is not likely to be the same for small VHGs over long durations as for large VHGs over short periods of time. Measurement of flow duration across a range of discharges is therefore needed to characterize the influence of flow variability on SGW exchanges rates.

6.3.3 An Analysis of Flow Variability Dependency with Basin Area

Both the duration and intensity of flows are expected to control SGW exchange rate as well as the spatial extent of the hyporheic zone. Comparison of flow variability for range of basin areas can provide scaling factors to judge how the strength and direction of SGW exchanges changes with system size.

In this analysis, time series of daily river flows from the Colorado (Arizona, USA) and the Loire (western France) basins were used to: (i) evaluate how SGW exchange scales with basin area in two contrasting climatic regimes, and (ii) compare the effect of arid and humid temperate climates on flow variability. River gauging stations were chosen to span a range of basin areas from 100 to 100 000 km^2, selecting as far as possible a common monitoring period in each basin, but giving priority to natural flow conditions. The duration of each time-series used was 10 years.

The Colorado River basin in southwestern USA is a ~489 000 km^2 catchment with headwaters in the Rocky Mountains. The Colorado drains mountainous and lowland arid and semi-arid terrain, and has been heavily modified to meet water-supply demands for agriculture, mining, and urban growth in the region. Discharge from the mainstem Colorado to the Gulf of California has dropped to a trickle as a result of this water use. Annual precipitation ranges nearly 1000 mm in the mountains, which falls mainly as snow, to under 200 mm in the deserts. Temperatures exhibit a similarly wide range (<0->45 °C), with cold winters in the mountains and hot, dry summers in the deserts. The basins selected for analysis ranged in area from 100 to just under 300 000 km^2, and are drained by unimpounded, free-flowing rivers.

The Loire River in western France drains 110 000 km^2 of gentle terrain in the west and highly eroded mountainous lands in the east that account for a quarter of the total area. The basin is covered with a patchwork of land uses from forested uplands to agricultural and urban areas on flat lands. Climate in this region is humid, with annual precipitation ranging from 700 mm in the plains to 1000 mm in the mountains, and is characterized by cool, rainy winters and mild summers. River flow alterations include hydropeaking in winter and abstractions for agricultural water supply in the summer; however, the latter impacts mainly the Loire mainstem. Basin selection covers a range from 100 to 110 000 km^2 in area, with nearly natural flows for <5000 km^2 catchments. The specific discharge for small to large Colorado and Loire basins, respectively, ranges from 0 to 4 and from 5 to 15 l s^{-1} km^{-2}.

Flow variability has two dimensions: the first reflects deviation from a mean value, and the second concerns the timing of given flow conditions. For the first dimension, the coefficient of variation (CV) was calculated from the discharge time series. This metric is a dimensionless measure of the dispersion around the mean discharge; hence, it can be used for comparison between basins and across spatial scales. Higher values of the CV for natural flow regimes often reflect a high ratio of peak-to-mean flows. The temporal distribution of flow fluctuations was assessed using mean event duration (*D*-value) and mean number of events per year (*N*-value) versus basin area. Events were defined as flows exceeding a threshold, with duration of exceedance computed for each event. Median discharge was used as the threshold because, by definition, it gives the flow value that is exceeded (or not reached, in the case of low-flow events) half of the time. The median reference is calculated only for the period of flow for intermittent streams to focus on water-movement indicators. To illustrate the dynamics of flow, the relationship between mean time of rise to peak flow and mean event-flow duration at each station was considered. To judge the magnitude with duration, the rate of change was calculated as the peak event flow divided by the median flow to give an *M*-value.

The comparative analysis of discharge time series revealed differences in flow variability for the arid/ semi-arid Colorado basin compared to the humid Loire basin. Overall, CV was greater in the arid basins than in the humid basins. CV decreased from small to large basins above a threshold of ~1000 km^2 in both climatic situations, although the pattern is more marked for the Colorado (Figure 6.3). Below this threshold, CV was positively correlated with basin size for the Loire basin. In contrast, the Colorado exhibited no clear relationship between CV and basin size for small basin areas. It may be that local basin features, like topography and geology, more strongly influence flow variability of small rivers in arid climates, but a regional study should be developed to confirm this assertion. These results suggest that a trend toward reduced flow variability with basin size is a general phenomenon. Considering SGW exchanges, these results lead to the expectation that in arid climates temporal gradients in water level will be greater and should induce more intense exchanges.

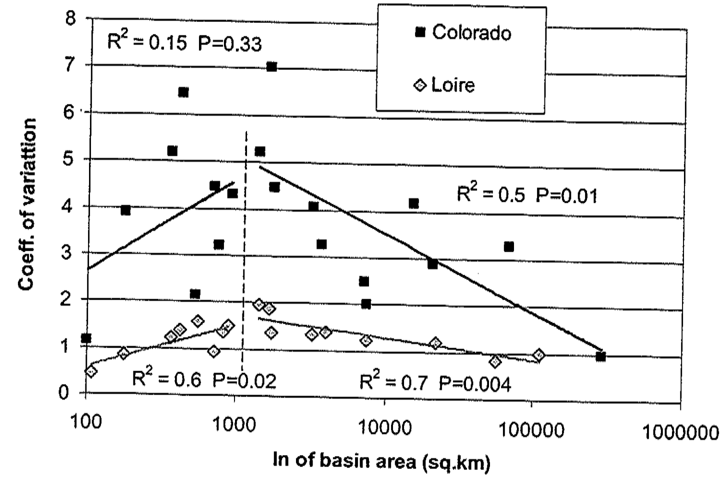

Figure 6.3 Coefficient of variation of stream flow as a function of discharge for variously sized catchments in the Colorado River basin, southwestern USA, and the Loire basin, France (coefficient of variation calculated from 10 years' data in each system.)

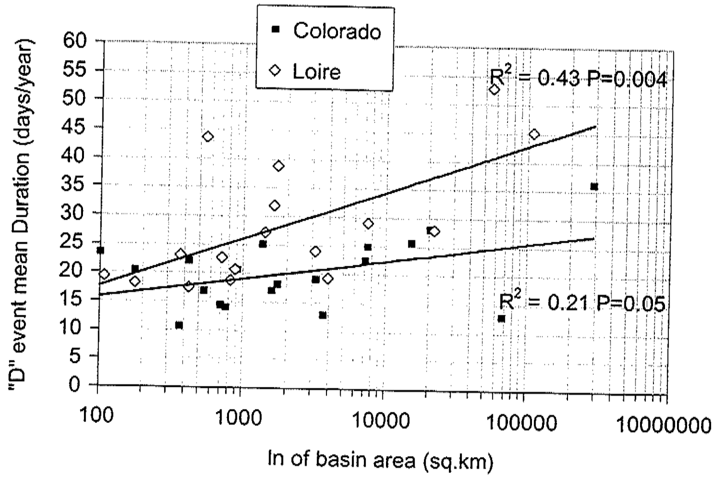

Figure 6.4 Mean event duration per year versus log of basin size, for variously sized catchments in the Colorado River basin, southwestern USA, and the Loire basin, France

As discussed earlier, the frequency and duration of flow fluctuations are expected to influence HGs and thus SGW exchanges. Mean event number per year decreases as mean event duration increases according to the mathematical relationships that link these variables (Figure 6.5), except for arid intermittent streams with no flow periods (out points from curve). Means of event duration and event number both significantly differed between climates; the probability that both belong to the same statistical population is <1 % and <3 %, respectively. Overall, the Colorado basin exhibits flow events with a mean duration of 20 days repeated on average nine times a year, whereas event duration for the Loire basin is 28 days and frequency is seven times per year.

The Colorado at its outlet (~300 000 km^2 basin area) shows a major change in mean event duration D-value, from 36 to 8 days, as a result of dam operation (white triangle). Such a value corresponds to basins <100 km^2 in area (Figure 6.5). D-Value also correlates positively with log basin area, with the strongest relationship in the humid climate (Figure 6.4). We conclude from this analysis, which is limited to a relatively small dataset but encompasses a wide range of basin areas, that event durations increase and number of events decrease as basin area increases.

Assuming that a large number of events favours increased SGW exchange (owing to abrupt changes in hydraulic gradient), event duration should determine total SGW exchange per unit distance. This hypothesis was tested by regressing the relative magnitude of events, calculated as the ratio for each event of the peak flow to the median flow, the event duration, and the time of rise to peak on basin area (Figure 6.6). Both Colorado and Loire data exhibit a similar pattern for the two indices, with almost the same range of values.

Relative flow magnitude gives an indirect measure of water-level increase in the river channel, since river cross sections are sized to easily transfer the median flow. Because log

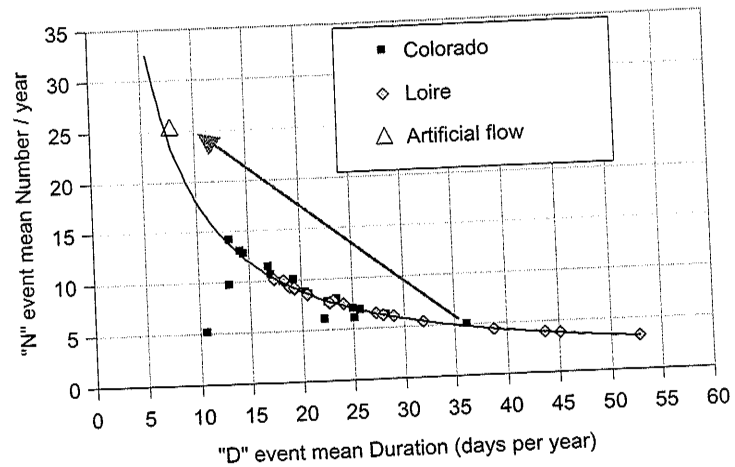

Figure 6.5 *Mean number of events per year versus event mean duration per year, for variously sized catchments in the Colorado River basin, southwestern USA, and the Loire basin, France*

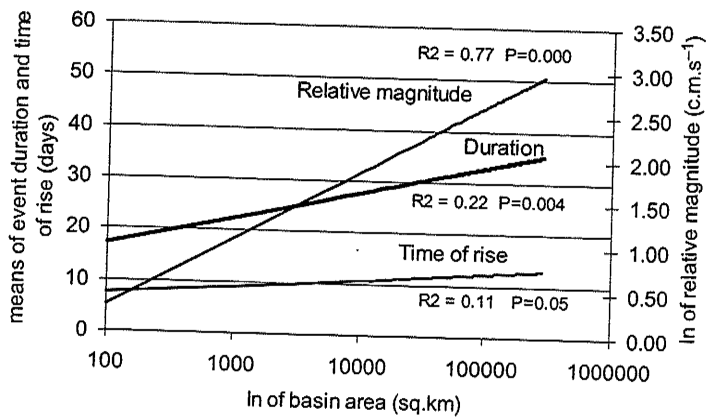

Figure 6.6 *Magnitude, duration, and time of rise to peak flow versus basin scale; regressions presented for Loire and Colorado Rivers combined*

relative magnitude is strongly correlated with log basin area ($R^2 = 0.77$; Figure 6.6), larger basins should exhibit larger water-level elevations during events as a percentage of median flow, and vertical hydraulic gradients between SW and GW should be correspondingly greater. Also, since event duration is positively related to basin area, event duration and relative magnitude are correlated (for the Loire and Colorado, $R^2 = 0.44$ and 0.22, respectively). Such a relation between magnitude and duration is clearly confirmed for maximum values and forms the basis for flood magnitude–duration–frequency analysis to calculate recurrence intervals of major events (Javelle *et al.*, 2002). Time of rise to peak flow is only weakly correlated with basin area (Figure 6.6) but the trend does imply that water level rises faster in small than in large basins. Again, rapid changes in water elevation might lead to strong, short-term vertical hydraulic gradients favouring SGW exchanges.

6.3.4 Linkage Between SGW and Flow Dynamics

Given the patterns of change in flow variability with the spatial scale that have been pointed out, it follows that rivers draining small- to medium-sized basins should provide nutrients to the hyporheic zone more efficiently than do rivers of larger basins. From our results it is not possible to get an idea on the 'quantity' of water exchanges, but clearly the temporal and spatial dimensions of concern are not the same for small to medium and large basin sizes. This has clear implications for the validation of ecological concepts at appropriate scales (Minshall, 1988).

Hydrologic dynamics described in the previous section interact with the fluvial landscape to create variability in the strength of SGW exchanges, with consequences for the structure and function of fluvial ecosystems. However, few studies are conducted for a range of scales and flow rates. The analysis presented here of how flow variability scales with basin area may provide a starting point for hypotheses about major controls of SGW exchanges for a range of fluvial ecosystem scales, considering duration (D), Frequency (N) and Intensity (M) of events over a frequent discharge like the median discharge in this example (Table 6.1).

Table 6.1 Hydrologic factors likely to control SGW exchanges at a range of basin areas, based on scaling analysis of changes in flow variability with basin area. For each basin area, the relevant spatial scale within the fluvial ecosystem, and the important biological and anthropogenic influences on SGW exchange, are listed

Basin area (km^2)	Hydrologic factors time scale	Indicative fluvial ecosystem dimension of concern	Biologic influences	Sensitive anthropogenic influences
>10 000	$D > 25$–45 days $N < 4$ days $M > 2$	Sector (hundredths of meters)	Humans	Large dams Flow diversion
1000 to 10 000	$D = 22$–35 days $N < 6$ days $M > 1$	Reach (tenths of meters)	Long-lived trees (evapo-transpiration) Beavers	Straightening Bridge construction
100 to 1000	$D = 20$–25 days $N < 8$ days $M > 0.5$	Channel unit (meters)	Riparian vegetation (coarse woody debris)	Bank incision Bank stabilization Canalization Large trash
<100	$D = 15$–20 days $N = 10$ days $M < 0.5$	Sub-unit (meter)	Fish bioturbation Algal mats	Introduction/ removal of species Channel modifications
<10	D^{**} = hours $N^{**} >> 10$ days $M^{**} << 0.5$	Particle (decimetre)	Invertebrate bioturbation	Pollution (clogging pores, killing inverts and microbiota) Sedimentation

(*) *D*: event mean duration per year, *N*: event mean number per year, *M*: event mean relative magnitude per year (log measure). ** *expected time scale, not tested*

6.4 Implications of Flow Variability for SGW Exchange and Fluvial Ecosystem Structure and Function

6.4.1 Material Delivery to and within Fluvial Ecosystems

The catchment is the ultimate source of nutrients and organic matter entering the river. As water flows from uplands to fluvial ecosystems, then downstream along riverine flow-paths, it transports chemical elements from one compartment or functional unit to another. Abiotic and biotic reactions within the catchment buffer material concentrations in the river via pore water; hence, concentrations of dissolved organic carbon (DOC) and non-reactive minerals (chemical signatures) of rivers are relatively stable and insensitive to catchment disturbances (Bormann and Likens, 1979; Neal *et al.*, 1992). More reactive substances are altered during upland–river transport. Differential export of organic carbon compounds from the soil to the river, for example, results from an interaction between

degradation reactions and adsorption, a concept reflected in the 'regional chromatography model' advanced by Hedges *et al.* (1986). Hedges *et al.* (1994) further suggest that greater attention should be paid to nitrogen (N) content as a factor modulating organic matter exports.

These material fluxes, both to and within fluvial ecosystems, are dependent upon seasonal distributions of hydrologic events (i.e., high flows), as well as vegetation activity and soil temperature. The mobile products of leaching, decomposition, and other terrestrial processes are transported in subsurface flow to the river. Thus, the hydrologic cycle strongly influences quality and quantity of nutrients and organic matter fluxes during water movement from catchment via subsoil waters to the river (Cirmo and McDonnell, 1997; Salmon *et al.*, 2001; McGlynn and McDonnell, 2003). This action is exerted on various scales within the catchment and fluvial ecosystem, and at some scales or in some rivers, the direction of fluxes may be reversed (i.e., from river to riparian zone; Marti *et al.*, 1997). Studies of nutrient dynamics require analyses of spatial and seasonal variations of transport through, and activity in, different permeable media, such as upland soil, the riparian zone, and the hyporheic zone. These dynamics are driven by the physical movement of water in the fluvial ecosystem as a whole. Each functional unit may work as a filter (mechanical, chemical and biochemical filters). Stronger active zones (hot spots) are places where filters are particularly effective.

6.4.2 Modulation of Nutrient and Organic Matter Delivery by the Riparian Interface Zone

The river is coupled with its catchment via the riparian zone or floodplain, whose nature and width modulate transfers of organic matter and nutrients (Gold *et al.*, 2001; Burt and Pinay, 2005). Floodplain width and development can vary along river courses; thus, there is variation in the capacity to modulate sediment or nutrient delivery to the river from the catchment during floods. Within the fluvial landscape, heterogeneity in both biotic activity and hydrologic properties strongly affects biogeochemical function. For instance, the riparian zone usually exhibits a high potential for denitrification, owing to high organic matter content and fine sediments favorable to denitrifying bacteria (Pinay *et al.*, 1990, 1995). However, at the ecosystem scale, zones of high denitrification potential can represent zones of low hydraulic conductivity. Therefore, the total capacity for N transformation within these active zones can be low (Figure 6.7).

Permeable media within the fluvial ecosystem act as biogeochemical reactors whose function varies with hydrologic conditions. For example, transport of organic matter from riparian soil to the river can be by lateral seepage or by episodic runoff (McDowell and Likens, 1988). In the former case, the organic matter is in prolonged contact with the mineral phase in soil interstices, leading to low concentrations. During storms, the system is short-circuited, and large quantities of organic matter leached from surface litter or vegetation are moved rapidly to the river without passing through soil horizons, where microbial uptake or fixation on mineral surfaces might have taken place. Under these conditions, the organic matter reaching the river is less degraded due to its short residence time in the soil. Such organic matter pulses are transitory and quickly absorbed, but in the stream rather than the soil. The organic matter residence time is a few days, or even a few hours.

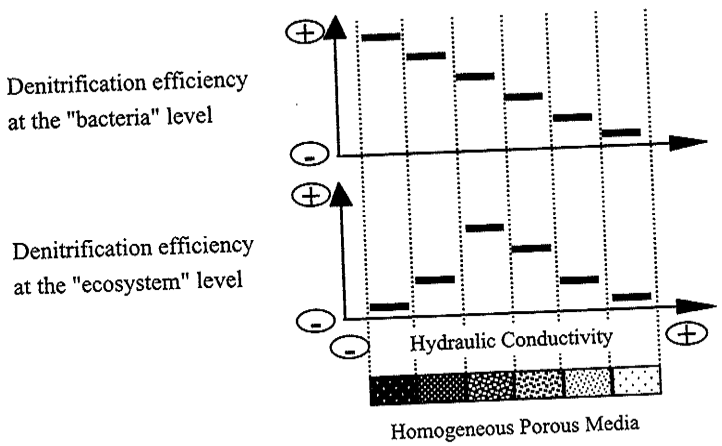

Figure 6.7 The whole-system capacity for denitrification (i.e., efficiency of the nitrogen 'filter') is a function of both bacterial efficiency (top) and hydrologic properties (bottom), since both high biological activity and substantial hydrologic flux are required for an effective nutrient filter

In the model just described, near-stream riparian zones are of considerable importance as an organic matter source to the river. High DOC concentrations associated with runoff from storms or snowmelt often come mainly from the near-stream riparian zones (Boyer *et al.*, 1997), whereas infiltration water has a more distant origin and tends to be lower in DOC concentration and more refractory. These suppositions are reasonable for soils of the Hubbard Brook Valley (New Hampshire, USA) with its impermeable horizon that functions like a podzol. Here, more river water comes from superficial horizons and deep infiltration is significant. The model requires testing in more porous soils.

6.4.3 In-stream Biogeochemical Function and Flow Variability

The hyporheic zone lies at the interface of the epigean and hypogean river subsystems, with its size dynamically determined by porosity and the volume of water interacting with the surface (Triska *et al.*, 1989). Dimensions of the hyporheic zone will change in response to flow variability, as shown above for our case study. Like SGW exchange rate, biogeochemical activity in the hyporheic zone changes in response to surface water flow and its variations (Stanley and Boulton, 1995; Valett *et al.*, 1996). The hyporheic zone can serve as a mechanical, physical and biochemical filter. Hyporheic sediments store and process organic matter and nutrients mostly received from exchange with surface water (Grimm and Fisher, 1984; Jones *et al.*, 1995a; Boulton *et al.*, 1998; Grimaldi and Chaplot, 2000). Riffle zones are important sites of SGW exchange (Speaker *et al.*, 1984; Pusch, 1996); downwelling zones supply organic matter that fuels heterotrophic microbial metabolism (Pusch and Schwoerbel, 1994; Jones *et al.*, 1995b; Mulholland *et al.*, 1997), which in turn supports a diverse and unique hyporheic community (Danielopol, 1989; Boulton *et al.*, 1992; Findlay *et al.*, 2003). Thus, temporal dynamics of hyporheic-zone biogeochemical processes are highly dependent upon SGW exchanges that affect delivery of these materials.

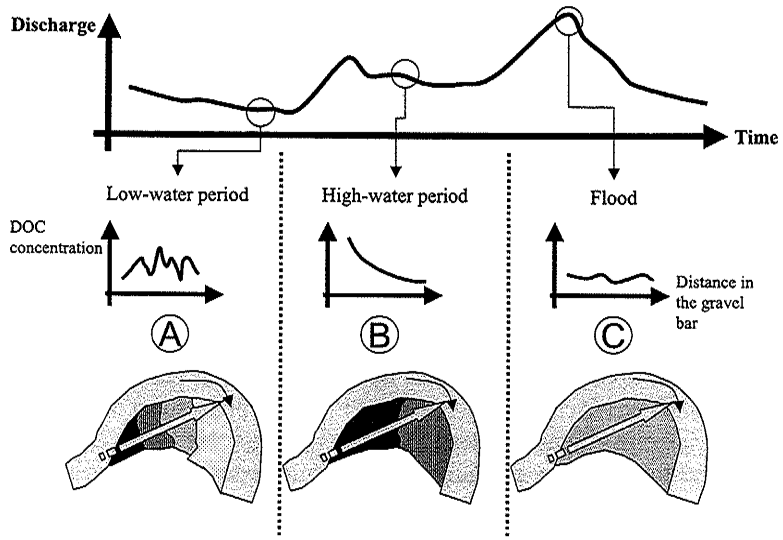

Figure 6.8 Changes in patterns of DOC within gravel-bar flowpaths under different flow conditions. Top: schematic of hydrograph. Middle: variation in DOC concentration with distance along flowpath. Bottom: Gravel-bar flowpath traversing (A) heterogeneous patchwork of habitats under low flow; (B) less heterogeneous gravel bar at high flow; and (C) less heterogeneous gravel bar during flood

Variations in flow can also influence biogeochemical function via effects on the strength or direction of SGW exchanges. An example is provided by DOC dynamics in a river gravel bar (Figure 6.8). Biogeochemical processes within the gravel bar result in strong retention of DOC, variable DOC patterns, or no change, depending on the magnitude of the hydrologic event. During the low flow period, DOC concentrations within the hyporheic zone are controlled by very local parameters such as grain size or organic matter richness of sediments. During floods, the hydraulic conductivity of the sediments can be increased by removal of very fine interstitial particles, and retention does not occur.

Finally, the flow regime controls biological nutrient use via its influence on plant and algal biomass in rivers. Large rivers with constant, slow flows can support water-column phytoplankton that directly use dissolved nutrients, whereas more variable flows restrict algal growth to fixed substrata. Biomass of attached algae or biofilms varies substantially owing to scour and export during high flows, followed by low-flow periods when biomass accumulates (Biggs and Close, 1989; Grimm and Fisher, 1989; Battin *et al.*, 2003a). It is this net growth that can account for a high rate of nutrient uptake from the water column (e.g., Grimm, 1987). However, the relationship between nutrient content of the water column and biofilm growth is not always direct (Ameziane *et al.*, 2002; Sauvage *et al.*, 2003). In turn, biofilms can have an effect on the rate of SGW exchange and other hydrodynamic variables like transient storage (Battin *et al.*, 2003b).

6.5 Conclusion

Dynamics of SGW exchange processes and associated ecosystem functions in river corridors clearly relate to hydrologic variability. At the local scale of a channel reach geomorphic unit, direction and magnitude of exchange were demonstrated to vary with discharge range and flow dynamics. Investigation of these dynamics for medium to large water courses was performed by generating hydrologic indices of flow variability for two contrasting regions, and examining how they changed with increase in basin area. The strength of scaling relationships depended to some extent upon climatic setting (arid or temperate). Biogeochemical process dynamics are likely to covary with these hydrologic gradients, based upon a literature survey of SGW exchange and ecosystem functions.

An ecohydrologic approach that marries hydrologic approaches to flow variability in space and time and ecological understanding of biotic responses can improve our understanding of fluvial ecosystems and lead to better management under increasing human manipulation and indirect impacts. Ecohydrology in this sense refers to a collaborative enterprise, with ecologists bringing understanding of ecosystem structure and function, and hydrologists bringing knowledge of energy and water fluxes, flow variability, and SGW exchange. Flow variability can affect fluvial ecosystems by changing the dynamics of SGW interactions that are key to biotic community structure and biogeochemical function at a wide range of scales. Concepts recognizing spatial heterogeneity and multiscaled phenomena that influence SGW interactions will be most useful to advancing understanding of fluvial ecosystems.

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References

Ameziane T, Garabetian F, Dalger D, Sauvage S, Dauta A, Capblancq J. 2002. Epilithic biomass in a large gravel-bed river (the Garonne, France): A manifestation of eutrophication? *River Research and Applications*, **18**: 343–354.

Battin TJ, Kaplan LA, Newbold JD, Cheng XH, Hansen C. 2003a. Effects of current velocity on the nascent architecture of stream microbial biofilms. *Applied and Environmental Microbiology*, **69**: 5443–5452.

Battin TJ, Kaplan LA, Newbold JD, Hansen CME. 2003b. Contributions of microbial biofilms to ecosystem processes in stream mesocosms. *Nature*, **426**: 439–442.

Biggs BJF, Close ME. 1989. Periphyton biomass dynamics in gravel bed rivers – the relative effects of flows and nutrients. *Freshwater Biology*, **22**: 209–231.

Bormann FH, Likens GE. 1979. Catastrophic disturbance and the steady-state in Northern Hardwood Forests. *American Scientist*, **67**: 660–669.

Boulton, AJ, 1993. Stream ecology and surface hyporhic hydrologic exchange – Implications, techniques and limitations. *Australian Journal of Marine and Freshwater Research*, **44**:553–564.

Boulton AJ, Valett HM, Fisher SG. 1992. Spatial-distribution and taxonomic composition of the hyporheos of several Sonoran Desert streams. *Archiv für Hydrobiologie*, **125**: 37–61.

Boulton AJ, Findlay S, Marmonier P, Stanley EH, Valett HM. 1998. The functional significance of the hyporheic zone in streams and rivers. *Annual Review of Ecology and Systematics*, **29**: 59–81.

Boyer EW, Hornberger GM, Bencala KE, McKnight DM. 1997. Response characteristics of DOC flushing in an alpine catchment. *Hydrological Processes*, **11**: 1635–1647.

Bunn SE, Thoms MC, Hamilton SK, Capon SJ. 2006. Flow variability in dryland rivers: Boom, bust and the bits in between. *River Research and Applications*, **22**: 179–186.

Burt TP, Pinay G. 2005. Linking hydrology and biogeochemistry in complex landscapes. *Progress in Physical Geography*, **29**: 297–316.

Calver A. 2001. Riverbed permeabilities: Information from pooled data. *Ground Water*, **39**: 546–553.

Cardenas MB, Wilson JL, Zlotnik VA. 2004. Impact of heterogeneity, bed forms, and stream curvature on subchannel hyporheic exchange. *Water Resources Research*, **40**: Art. No. W08307.

Cirmo CP, McDonnell JJ. 1997. Linking the hydrologic and biogeochemical controls of nitrogen transport in near-stream zones of temperate-forested catchments: a review. *Journal of Hydrology*, **199**: 88–120.

Connell JH, Wayne PS. 1983. On the evidence needed to judge ecological stability or persistence. *The American Naturalist*, **121**: 798–824.

Connell JH. 1978. Diversity in tropical rain forests and coral reefs. *Science*, **199**: 1302–1310.

Dahm CN, Grimm NB, Marmonier P, Valett HM, Vervier P. 1998. Nutrient dynamics at the interface between surface waters and groundwaters. *Freshwater Biology*, **40**: 427–451.

Danielopol DL. 1989. Groundwater fauna associated with riverine aquifers. *Journal of the North American Benthological Society*, **8**: 18–35.

Dent CL, Schade JD, Grimm NB, Fisher SG. 2000. Subsurface influences on surface biology. In J.B. Jones, Jr. and P.J. Mulholland (Editors), *Streams and Ground Water*. Academic Press, San Diego, USA.

Dent CL, Grimm NB, Fisher SG. 2001. Multiscale effects of surface–subsurface exchange on stream water nutrient concentrations. *Journal of the North American Benthological Society*, **20**: 162–181.

Elwood JW, Newbold JD, O'Neill RV, Van Winkle W. 1983. Resource spiraling: an operational paradigm for analyzing lotic ecosystems. In T.D. Fontaine and S.M. Bartell (Editors), *Dynamics of Lotic Ecosystems*. Ann Arbor Science, AnnArbor, Michigan, USA, pp. 3–28.

Evans EC, Petts GE. 1997. Hyporheic temperature patterns within riffles. *Hydrological Sciences Journal–Journal Des Sciences Hydrologiques*, **42**: 199–213.

Fellows CS, Valett HM, Dahm CN. 2001. Whole-stream metabolism in two montane streams: Contribution of the hyporheic zone. *Limnology and Oceanography*, **46**: 523–531.

Findlay SEG, Sinsabaugh RL, Sobczak WV, Hoostal M. 2003. Metabolic and structural response of hyporheic microbial communities to variations in supply of dissolved organic matter. *Limnology and Oceanography*, **48**: 1608–1617.

Fisher SG, Grimm NB, Marti E, Holmes RM, Jones JB. 1998. Material spiraling in stream corridors: A telescoping ecosystem model. *Ecosystems*, **1**: 19–34.

Gold AJ, Groffman PM, Addy K, Kellogg DQ, Stolt M, Rosenblatt AE. 2001. Landscape attributes as controls on ground water nitrate removal capacity of riparian zones. *Journal of the American Water Resources Association*, **37**: 1457–1464.

Gregory SV, Swanson FJ, McKee WA, Cummins KW. 1991. An ecosystem perspective of riparian zones. *Bioscience*, **41**: 540–551.

Grimaldi C, Chaplot V. 2000. Nitrate depletion during within-stream transport: Effects of exchange processes between streamwater, the hyporheic and riparian zones. *Water Air and Soil Pollution*, **124**: 95–112.

Grimm NB, Fisher SG. 1984. Exchange between interstitial and surface-water: implications for stream metabolism and nutrient cycling. *Hydrobiologia*, **111**: 219–228.

Grimm NB. 1987. Nitrogen dynamics during succession in a desert stream. *Ecology*, **68**: 1157–1170.

Grimm NB, Fisher SG. 1989. Stability of periphyton and macroinvertebrates to disturbance by flash floods in a desert stream. *Journal of the North American Benthological Society*, **8**: 293–307.

Harvey JW, Bencala, KE. 1993. The effect of streambed topography on surface–subsurface water exchange in mountain catchments. *Water Resources Research*, **29**: 89–98.

Hedges JI, Clark WA, Quay PD, Richey JE, Devol AH, Santos UD. 1986. Compositions and fluxes of particulate organic material in the Amazon River. *Limnology And Oceanography*, **31**:717–738.

Hedges JI, Cowie GC, Richey JR, Quay PD. 1994. Origins and processing of carbohydrates and amino-acids in the Amazon River. Abstracts of papers of *The American Chemical Society*, **207**: 63-GEOC.

Hildrew AG, Townsend CR. 1987. Organization in freshwater benthic communities. In J.H.R. Gee and P.S. Giller (Editors), *Organization of Communities, Past and Present*. 27th Symposium of the British Ecological Society. Blackwell Scientific Publications, Oxford, England, pp. 347–371.

Javelle P, Ouarda TBMJ, Lang M, Bobee B, Galea G, Gresillon JM. 2002. Development of regional flood-duration–frequency curves based on the index-flood method. *Journal of Hydrology*, **258**: 249–259.

Jones JB, Fisher SG, Grimm NB. 1995a. Nitrification in the hyporheic zone of a desert stream ecosystem. *Journal of the North American Benthological Society*, **14**: 249–258.

Jones JB, Fisher SG, Grimm NB. 1995b. Vertical hydrologic exchange and ecosystem metabolism in a Sonoran Desert stream. *Ecology*, **76**: 942–952.

Lafont M, Vivier A, Nogueira S, Namour Ph, Breil P. 2006. Surface and hyporheic oligochaete assemblages in a French suburban stream. *Hydrobiologia*, **564**: 183–193.

Maidment DR. 1993. Chapter V in *Handbook of Hydrology*, McGraw-Hill, New York, pp. 5.1–5.51.

Malcolm IA, Soulsby C, Youngson AF, Hannah DM, McLaren IS, Thorne A. 2004. Hydrological influences on hyporheic water quality: Implications for salmon egg survival. *Hydrological Processes*, **18**: 1543–1560.

Marti E, Grimm NB, Fisher SG. 1997. Pre- and post-flood retention efficiency of nitrogen in a Sonoran Desert stream. *Journal of the North American Benthological Society*, **16**: 805–819.

Marti E, Fisher SG, Schade JD, Grimm NB. 2000. Flood frequency and stream-riparian linkages in arid lands. In J.B. Jones, Jr. and P.J. Mulholland (Editors), *Streams and Ground Waters*. San Diego, Academic Press.

McClain ME, Boyer EW, Dent CL, Gergel SE, Grimm NB, Groffman PM, Hart SC, Harvey JW, Johnston CA, Mayorga E, McDowell WH, Pinay G. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. *Ecosystems*, **6**: 301–312.

McDowell WH, Likens GE. 1988. Origin, composition, and flux of dissolved organic carbon in the Hubbard Brook valley. *Ecological Monographs*, **28**: 177–195.

McGlynn BL, McDonnell JJ. 2003. Role of discrete landscape units in controlling catchment dissolved organic carbon dynamics. *Water Resources Research*, **39(11)**:1310.SCW 2-1-SCW 2-20.

Minshall GW. 1988. Stream ecosystem theory: A global perspective. *Journal of the North American Benthological Society*, **7**: 263–288.

Mulholland PJ, Steinman AD, Elwood JW. 1990. Measurement of phosphorus uptake length in streams: comparison of radiotracer and stable PO4 releases. *Canadian Journal of Fisheries and Aquatic Sciences*, **47**: 2351–2357.

Mulholland PJ, Marzolf ER, Webster JR, Hart DR, Hendricks SP. 1997. Evidence that hyporheic zones increase heterotrophic metabolism and phosphorus uptake in forest streams. *Limnology and Oceanography*, **42**: 443–451.

Neal C, Neal M, Warrington A, Ávila A, Piñol J, Rodà F. 1992. Stable hydrogen and oxygen studies of rainfall and streamwaters for two contrasting holm oak areas of Catalonia, northeastern Spain. *Journal of Hydrology*, **140**: 163–178.

Pinay G, Decamps H, Chauvet E, Fustec E. 1990. Functions of ecotones in fluvial systems. In R. J. Naiman and H. Decamps (Editors), *Ecology and Management of aquatic–terrestrial ecotones*. UNESCO and Parthenon Publishing Group, Paris, pp. 141–169.

Pinay G, Ruffinoni C, Fabre A. 1995. Nitrogen cycling in two riparian forest soils under different geomorphic conditions. *Biogeochemistry*, **30**: 9–29.

Petts G, Nienhuis PH, Tockner K, Brittain J, Breil P, Soulsby C, Wood JP, Ledger ME, Baker A, Capra H, Sadler J, Tabacchi E, Baptist MJ. 2005. Emerging concepts for integrating human and environmental water needs in river basin management. *US Army European Research Office*. WQTS final report. 14 sections. http://el.erdc.usace.army.mil/elpubs/pdf/trel05-13.pdf.

Poff NL. 1997. Landscape filters and species traits: Towards mechanistic understanding and prediction in stream ecology. *Journal of the North American Benthological Society*, **16**: 391–409.

Poff NL, Olden JD, Pepin DM, Bledsoe BP. 2006. Placing global stream flow variability in geographic and geomorphic contexts. *River Research and Applications*, **22**: 149–166.

Pusch M. 1996. The metabolism of organic matter in the hyporheic zone of a mountain stream, and its spatial distribution. *Hydrobiologia*, **323**: 107–118.

Pusch M, Schwoerbel J. 1994. Community respiration in hyporheic sediments of a mountain stream (Steina, Black Forest). *Archiv für Hydrobiologie*, **130**: 35–52.

Rouch R, Mangin A, Bakalowicz M, Dhulst D. 1997. The hyporheic zone: Hydrogeological and geochemical study of a stream in the Pyrenees mountains *Internationale revue der gesamten Hydrobiology*, **82**: 357–378.

Ruysschaert F, Breil P. 2004. Assessment of the hyporheic fluxes in a headwater stream exposed to combined sewer overflows, *Proceeding of the Fifth International Symposium on Ecohydraulics* 12–17 September 2004, Madrid, pp. 1148–1153.

Salmon CD, Walter MT, Hedin LO, Brown MG. 2001. Hydrological controls on chemical export from an undisturbed old-growth Chilean forest. *Journal of Hydrology*, **253**: 69–80.

Sauvage S, Teissier S, Vervier P, Ameziane T, Garabetian F, Delmas F, Caussade B. 2003. A numerical tool to integrate biophysical diversity of a large regulated river: Hydrobiogeochemical bases. The case of the Garonne River (France). *River Research and Applications*, **19**: 181–198.

Savant SA, Reible DD, Thibodeaux LJ. 1987. Convective-transport within stable river sediments. *Water Resources Research*, **23**: 1763–1768.

Southwood TRE. 1977. Habitat, templet for ecological strategies – presidential-address to the British Ecological Society, 5 January 1977. *Journal of Animal Ecology*, **46**: 337–365.

Speaker RW, Moore K, Gregory SV. 1984. Analysis of the process of retention of organic matter instream ecosystems. *Verhandlungen Internationale Vereinigung Limnologie*, **22**: 1835–1841.

Stanford JA, Gonser T. 1998. Rivers in the landscape: Riparian and groundwater ecology – Preface. *Special Issue of Freshwater Biology*, **40**: 401–401.

Stanford J, Ward JV. 1988. The hyporheic habitat of river ecosystems. *Nature*, **335**: 64–66.

Stanford JA, Ward JV. 1993. An ecosystem perspective of alluvial rivers: Connectivity and hyporheic corridor. *Journal of the North American Benthological Society*, **12**: 48–60.

Stanley EH, Boulton AJ. 1995. Hyporheic processes during flooding and drying in a Sonoran Desert stream. 1. Hydrologic and chemical-dynamics. *Archiv für Hydrobiologie*, **134**: 1–26.

Thibodeaux LJ, Boyle JD. 1987. Bedform-generated convective transport in bottom sediment. *Nature*, **325**: 341–343.

Thoms MC. 2006. Variability in riverine ecosystems. *River Research and Applications*, **22**: 115–121.

Townsend CR. 1989. The patch dynamics concept of stream community ecology. *Journal of the North American Benthological Society*, **8**: 36–50.

Triska FJ, Kennedy VC, Avanzino RJ, Zellweger GW, Bencala KE. 1989. Retention and transport of nutrients in a 3rd-order stream in northwestern California: hyporheic processes. *Ecology*, **70**: 1893–1905.

Valett HM, Morrice JA, Dahm CN, Campana ME. 1996. Parent lithology, surface–groundwater exchange, and nitrate retention in headwater streams. *Limnology and Oceanography*, **41**: 333–345.

White DS. 1990. Biological relationships to convective flow patterns within stream beds. *Hydrobiologia*, **196**: 149–158.

Winter TC. 2001. The concept of hydrologic landscapes. *Journal of the American Water Resources Association*, **37**: 335–349.

Wroblicky GJ, Campana ME, Valett HM, Dahm CN. 1998. Seasonal variation in surface–subsurface water exchange and lateral hyporheic area of two stream–aquifer systems. *Water Resources Research*, **34**: 317–328.