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ENVIRONMENTAL IMPACTS IN ARID AND SEMIARID FLOODPLAINS

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The interaction of groundwater with surface water is an important process for maintaining ecosystems. The hyporheic zone, the transition region between stream and subsurface water, represents an important interface between terrestrial and aquatic ecosystems. When subsurface water interacts with stream water in this zone, the characteristics of each are blended and new gradients are established, especially for contaminants. Groundwater-surface water interaction affects the ecology of surface water by sustaining streamflow during periods of low flow, moderating water level fluctuations of groundwater, surface water, and maintaining wetlands which serve as habitat for a myriad of wildlife. The interaction also helps stabilize stream water temperature as well as the concentrations of nutrients and other organic / inorganic compounds. The variability in physical and chemical characteristics between upwelling and downwelling zones influences the local ecology within the zone. With the growing demand for sustainable management and utilization of natural resources, a better understanding of all components of the ecosystem, such as the linkage between groundwater and surface water, becomes imperative. The evolving study of the hyporheic zone function will necessitate an increase in basic research into hydraulic considerations, an identification of regional representative sites with contaminated hyporheic zones, and a better understanding of the ecology of the species within the zone. This article is therefore intended to review fundamental concepts of ecohydrology of the interaction of groundwater with surface water in semiarid floodplains, and discuss the relevance of this interaction to the sustainable management of water resources in watersheds.

INTRODUCTION

The floodplain of a river is a relatively level area on both sides of the stream channel (Figure 1) that carries excess waters the main channel cannot handle during high flow periods. The floodplain allows flood water to spread out, thus decreasing flow velocity and reducing the flood water's potential energy. Floodplains often contain wetlands, which function to slow and filter the flood water. Wetlands also provide habitat for a diversity of wildlife.

Beneath the stream channel and floodplain is the interface zone between groundwater and surface water, the transition from a terrestrial ecosystem to an aquatic ecosystem. The technical name for this zone in flowing aquatic systems is the "hyporheic" zone. This zone of water and solute exchange between groundwater and surface water represents an ecotone, the crossing point between two distinct ecosystems where characteristics such as species and habitats of both systems overlap. The biota in the hyporheic zone is called "hyporheos". The hyporheic zone between groundwater and surface water is becoming an important consideration for environmental scientists, ecologists, geologists, hydrologists, and regulators. When groundwater interacts with surface water, the characteristics of each are blended and new gradients are established. Any contaminants contained within groundwater discharge can affect the quality of surface water.

Activities such as agriculture, urban and industrial development, drainage of land surfaces, modifications to river valleys, and global warming commonly affect the distribution, quantity, and chemical quality of water resources. Current environmental programs typically evaluate groundwater and surface water as separate environmental entities. Nevertheless, it is gradually being realized that it is necessary to look at the "big ecological picture" using a watershed approach. The hyporheic zone then takes on an added importance as the hydrologic continuum connecting groundwater and surface water.

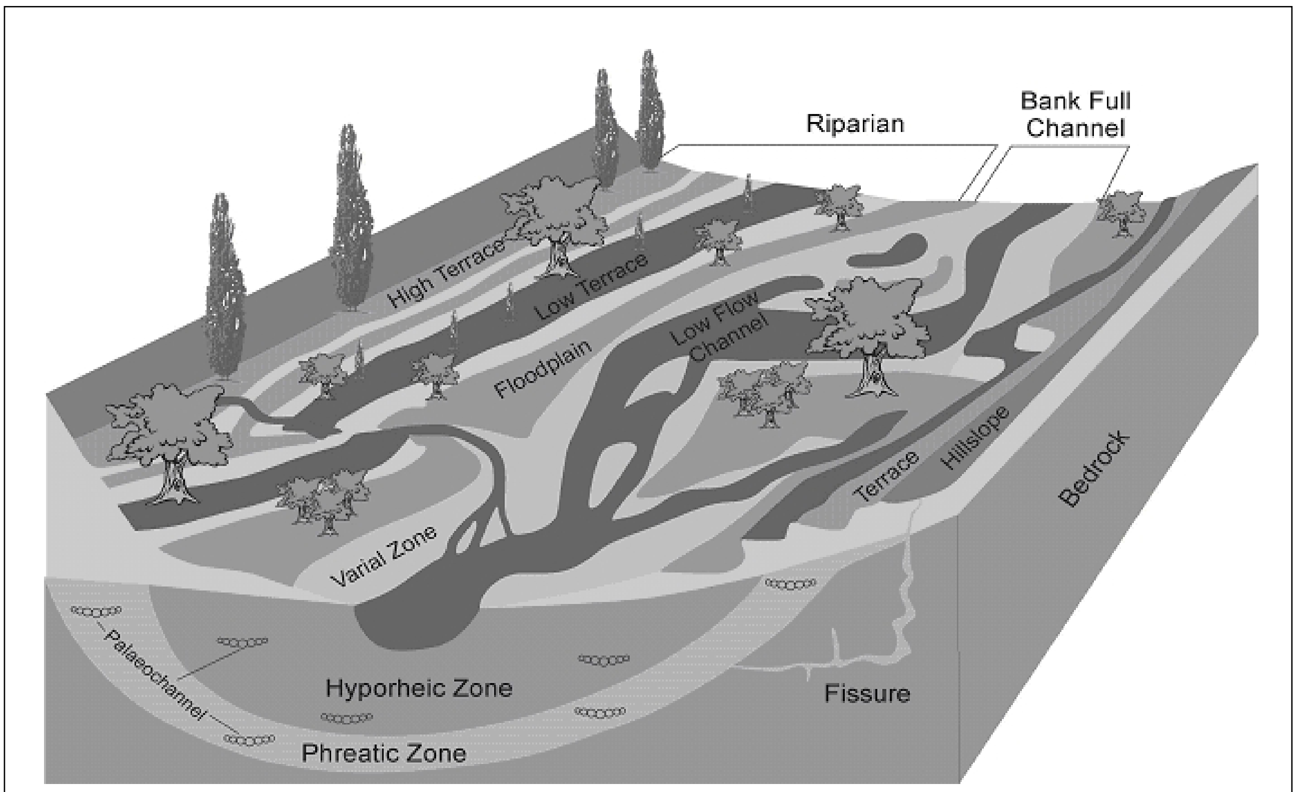

Figure 1. Hyporheic zone in the floodplain.

Understanding contaminant fate and transport within the hyporheic zone is necessary to evaluate impacts on surface waters. There is a need for investigations of groundwater and surface water to be integrated and to incorporate recent advances in the understanding of the hyporheic zone (Figure 1).

Ecological risk assessments for surface-water bodies often focus on the water column and surficial sediments. By focusing only on these areas, impacts on the hyporheic zone ecosystem are largely ignored. However, the hyporheic ecosystem provides important ecological structure and function moderated by both the groundwater and the surface water ecosystems. Therefore, it is important to examine the hyporheic zone when conducting risk assessments.

HYDROGEOLOGICAL CHARACTERISTICS OF FLOODPLAINS

Rivers may be categorized on the basis of discharge, for which velocity, width, and depth are the key variables. These elements form the basis of the hydraulic geometry of a river channel (Leopold and Wolman, 1964). Rivers may also be categorized on the basis of sediment load, for which gradient, grain size distribution of bed material, meander wavelength; width, depth, and sinuosity are important parameters. Stable alluvial channels usually possess meandering formation (Schumm, 1968). In essence, the channel morphology and the fluvial depositional system of the alluvial valley are controlled by the topography and the composition of the older rocks and sediments through which the river and its tributaries flow.

In general, floodplains display the following characteristics as one proceeds downstream: (a) a decreasing longitudinal channel and valley slope, (b) an increase in sinuosity, (c) a decrease in the ratio of bedload to total sediment load, (d) a decrease in the grain size of transported material, and (e) an increase in discharge.

At their upstream parts, rivers are commonly braided and fluvial systems are dominant. Bedload fluvial systems have a high width-to-depth ratio and consist primarily of channel and channel flank deposits with floodplain facies being subordinate (Galloway and Hobday, 1983). In some cases, the water table is below the water level in the river, allowing influent conditions (i.e. recharge of groundwater by surface water).

As the channel gradient decreases downstream, mixed-load fluvial conditions tend to develop. The width to depth ratio of the channel decreases, and the sinuosity increases. Sand percentages remain high in channel fill deposits along the channel axis, but the overall sand percentage is around 20% to 40%; the water table is closer to the surface and is usually hydraulically connected to the river.

At the downstream parts of an alluvial valley, gentle gradients and suspended load depositional systems usually prevail. Sinuosity is high, and natural levees are well developed. Sand percentages are low, and water tables are usually shallow.

Another important type of fluvial depositional environment is the valley fill system. Valley fill systems occur where bedrock walls bound the river and thereby restrict channel bank and bed erosion, and lateral river movement. Meandering can occur, but only within the confines of the valley. Coarser channel fill deposits dominate over finer floodplain and over bank facies. The resulting alluvial package contains a high percentage of sand and gravel and resembles a facies assemblage usually associated with bed load streams.

When the terrace deposits are in hydrologic connection with the alluvium, the two units are considered to be one aquifer. Cross sections through the alleviated portion of a river valley tend to display an overall fining upward sequence, the coarsest material on the bottom being of gravel size (Sharp, 1988). This arrangement is the result of changing sediment load in rivers that have responded to Pleistocene changes in climate and base level by adjusting their channel gradients. Rivers respond to lower base levels during periods of glaciation by increasing their gradients. This, in turn, has increased the average size of suspended load and bed load material in rivers. As glaciers retreated, sea level rose, gradients decreased, and rivers deposited their suspended material, alluviating their valleys.

GROUNDWATER FLOW IN THE FLOODPLAIN

Groundwater in floodplain aquifers is typically unconfined, but near surface permeability variations may create both confined and unconfined conditions (Ayers, 1989). As a result of the general fining upward trend in grain size, the hydraulic conductivity of alluvial aquifers tends to increase with depth (Sharp, 1988). The base of many alluvial aquifers consists of low permeability bedrock or clay. In these instances, the groundwater contribution to the alluvium from bedrock is considered negligible, but there are many situations where the alluvium overlies and is in hydraulic connection with other aquifers.

Both Hubbert (1940) and Toth (1963) point out the controlling importance of topography on steady state, unconfined, groundwater flow in river basins. In a basin, with homogeneous and isotropic geologic conditions, groundwater flows from recharge areas on the topographic highs to the discharge areas at the topographic lows. Freeze and Witherspoon (1967) discussed the importance of heterogeneity and anisotropy on groundwater flow in hypothetical valleys where ground water flow was topographically controlled. These authors considered only two-dimensional flow in vertical sections parallel to the hydraulic gradient and transverse to the longitudinal profile of the river. The results are valid only for the case where the longitudinal profile of the valley is insignificant compared to the lateral slope of the valley.

Figure 2 portrays an end-member situation where all groundwater flows toward the river in a direction that is essentially normal to the surface flow. In Figure 2, there is no component of underflow; all groundwater in the reach flows to the river. This idealized view is common in the literature and forms the conceptual basis for many analytical and numerical model studies that consider groundwater flow to a river. In addition, these models commonly require that the stream be fully penetrating. This conceptualization may be justified in many cases, however, near the river, the angle at which the equipotentials approach the stream may vary significantly in both time and space. Field observations indicate that a significant underflow component can be found in many stream aquifer systems (Grannemann and Sharp, 1979, Rosenshein, 1988). Regionally, away from the river (where equipotentials are in a quasi steady state), groundwater flow is not necessarily at right angles to the direction of surface flow.

CLASSIFICATION OF AQUIFERS IN FLOODPLAIN

If one wishes to identify or quantify the underflow or baseflow component of groundwater in a given stream aquifer reach, a reproducible definition is required. Figure 3 schematically represents one hypothetical equipotential (f) crossing a stream. The river is depicted as an effluent or gaining stream (equipotentials pointing downstream are characteristic of influent or losing

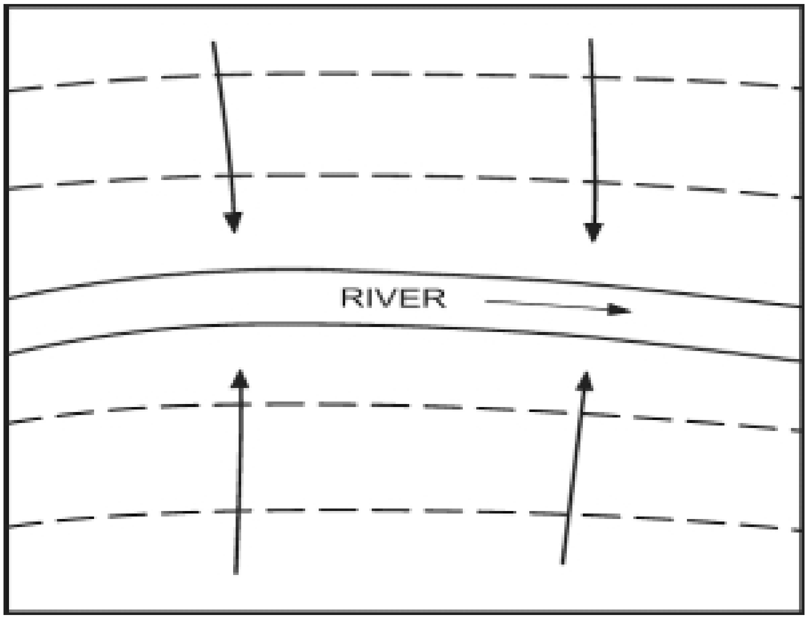

Figure 2. Groundwater flow to the stream.

streams). The equipotentials cross the river at some angle that deviates from the normal. This requires that there be two components of the specific discharge or Darcy flux vector q: a baseflow component (q_n) normal to the river (which may be positive or negative depending on whether the stream is influent or effluent) and a downstream component (q_u) that defines the underflow. Note that this base flow component designation refers only to the direction of flow and not to the quantity of water present at low flow in a stream. The magnitude of the underflow component is a measure of the degree to which the groundwater flux exhibits the tendency to travel downstream. Under these idealized conditions, the magnitudes of vectors can only be used as relative measures at specific reaches. Rivers are seldom straight for any great distance and alluvial groundwater eventually discharges as evapotranspiration or to the river at some distance downstream. This definition requires that another groundwater flow end member exist; the case where all groundwater is underflow (Figure 4). In this situation, all groundwater is in the downstream direction and none contributes to surface flow.

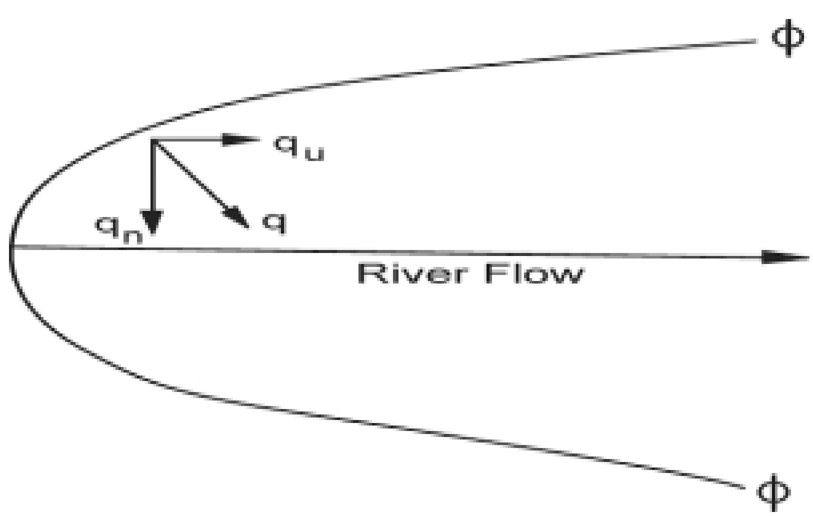

Figure 3. Underflow (q_u) and baseflow (q_n) components of groundwater flow.

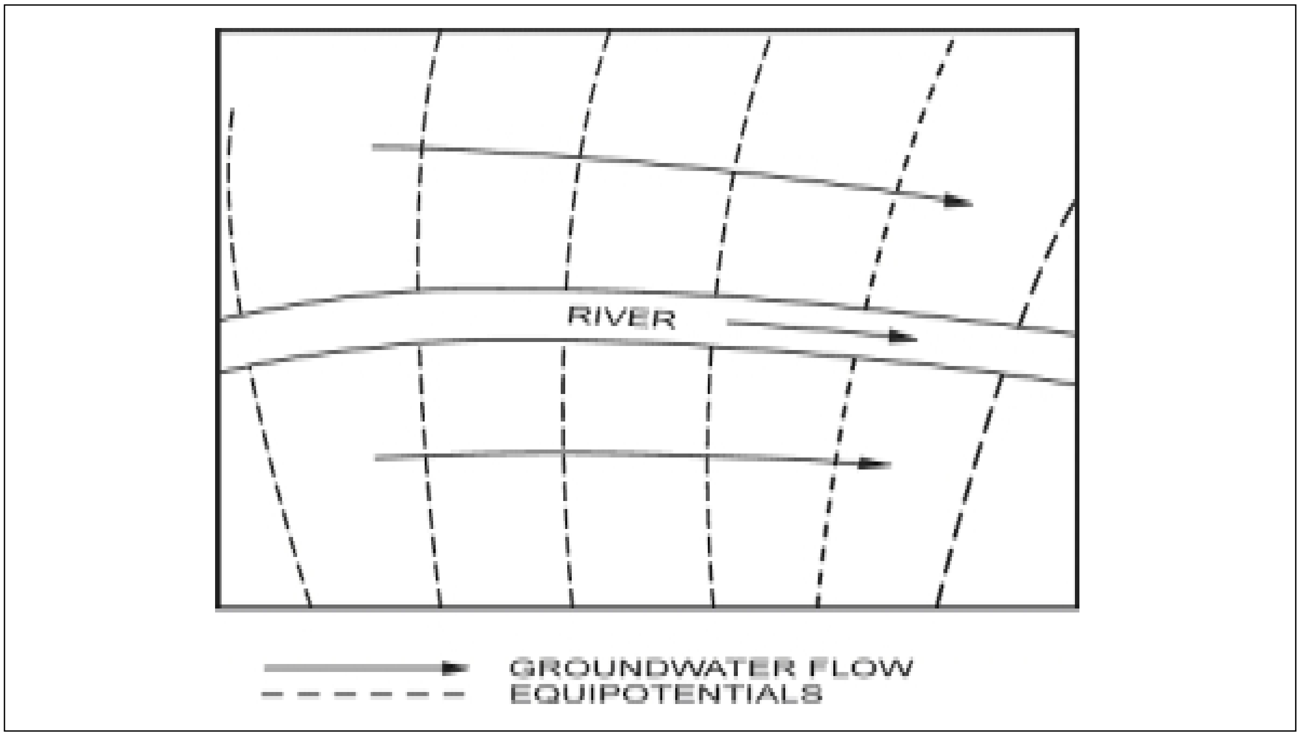

Figure 4. Groundwater parallel to stream.

An examination of field examples of floodplain systems reveals that they can be classified by their predominant regional groundwater flow component as, 1) baseflow component dominated, 2) underflow component dominated, and 3) mixed flow. The predominant groundwater flow direction in an alluvial aquifer may vary rapidly close to the river.

Underflow component dominated systems have regional equipotentials that are approximately perpendicular to the river. Examples of underflow component dominated are shown in Figure 5. In each case the lines of equal head are approximately normal to the river. Baseflow component dominated systems have regional equipotentials that are nearly parallel to the river. Examples of baseflow component dominated aquifers are shown in Figure 6**.** The equipotentials are closely parallel to the river, indicating that the baseflow component is large. The underflow component is correspondingly small.

Two criteria were used to classify mixed flow systems. First, if no clear underflow component or baseflow component predominance was noted over the study reach, the aquifer system was denoted as mixed. Second, some mixed flow systems have distinct and different orientations at local (near river) and regional scales.

IDENTIFICATION AND MEASUREMENT OF THE INTERACTION

The methods developed so far for the quantification of groundwater – surface water interactions are extremely complex, resource intensive, and require specialized knowledge to use them. Tools for identification of the presence of groundwater interaction with surface water range from inexpensive to resource intensive, and may be moderate to highly complex to use. First, a topographic map and remote sensing techniques (Bobba, et al., 1992, Becker, 2006), braided channels, ancient stream channels, and dense vegetation may indicate a groundwater – surface water interaction zone. Next, vegetation type, and the presence of algae along shallow edges of waterways may point to a groundwater surface water interaction zone (Gordon et al., 1992).

Figure 7 shows an example of mixed flow system. Some parts of the flow field are baseflow component dominated, whereas other parts are underflow component dominated.

Various probes may be used to measure changes within the channel, which may indicate the points of groundwater-surface water interaction. Temperature probes are commonly used to indicate the influence of groundwater on surface water. Hyporheic probes may be used to measure interstitial flow rates and changes in hydraulic gradient. Also, the potential for groundwater and surface water to interact, which is indicated by change in hydraulic head, may be measured using mini-piezometers (Brunke and Gonser, 1997).

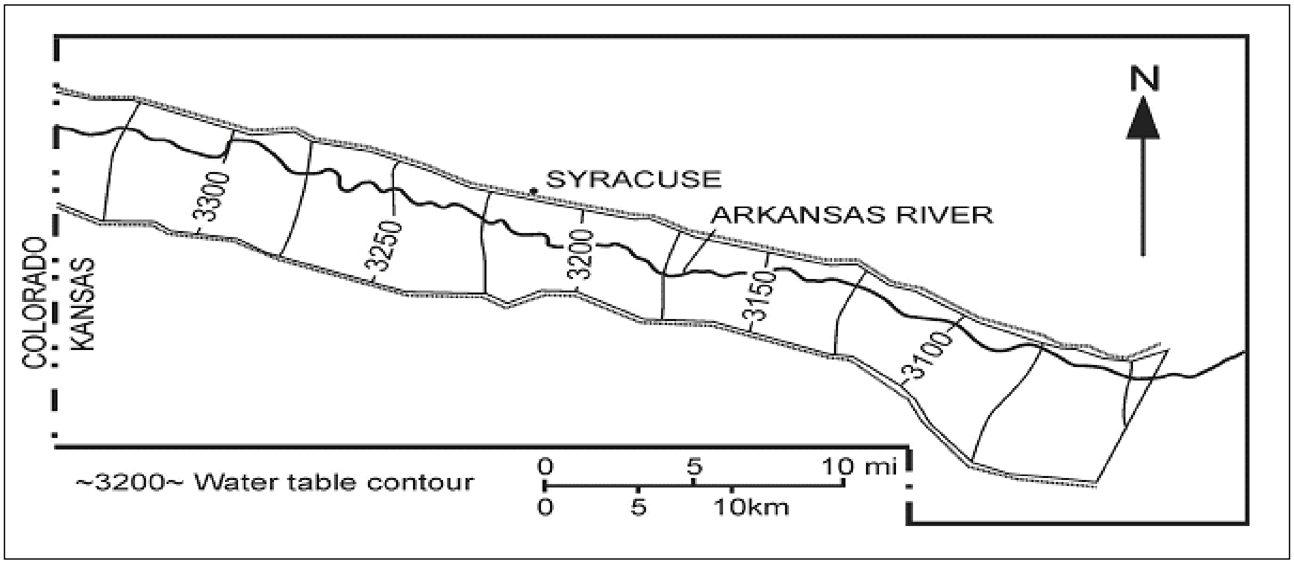

Figure 5. Example of underflow component: Upper Arkansas Valley alluvial aquifer, Kansas (Baker and Grootjans, 1996).

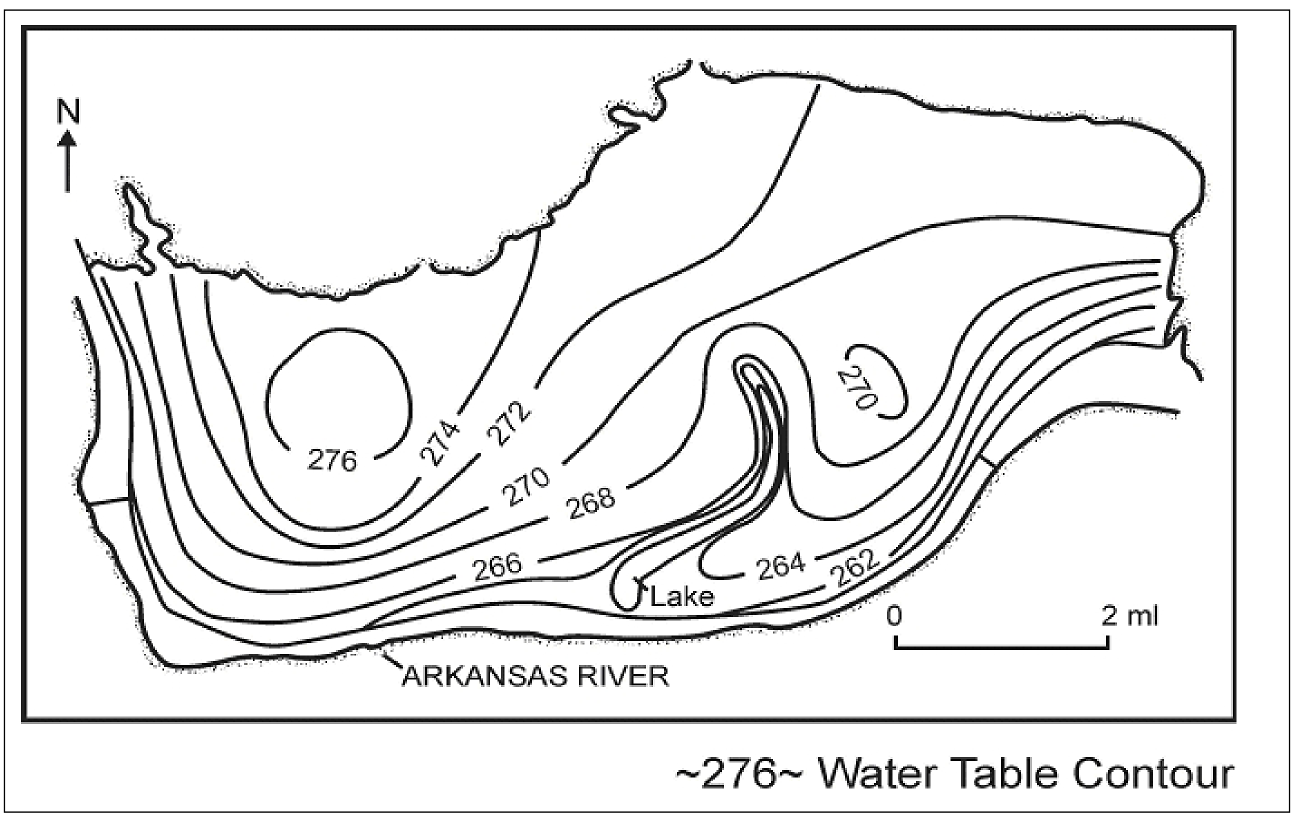

Figure 6. Example of baseflow component: Lower Arkansas River alluvial aquifer (Bedinger et al., 1983).

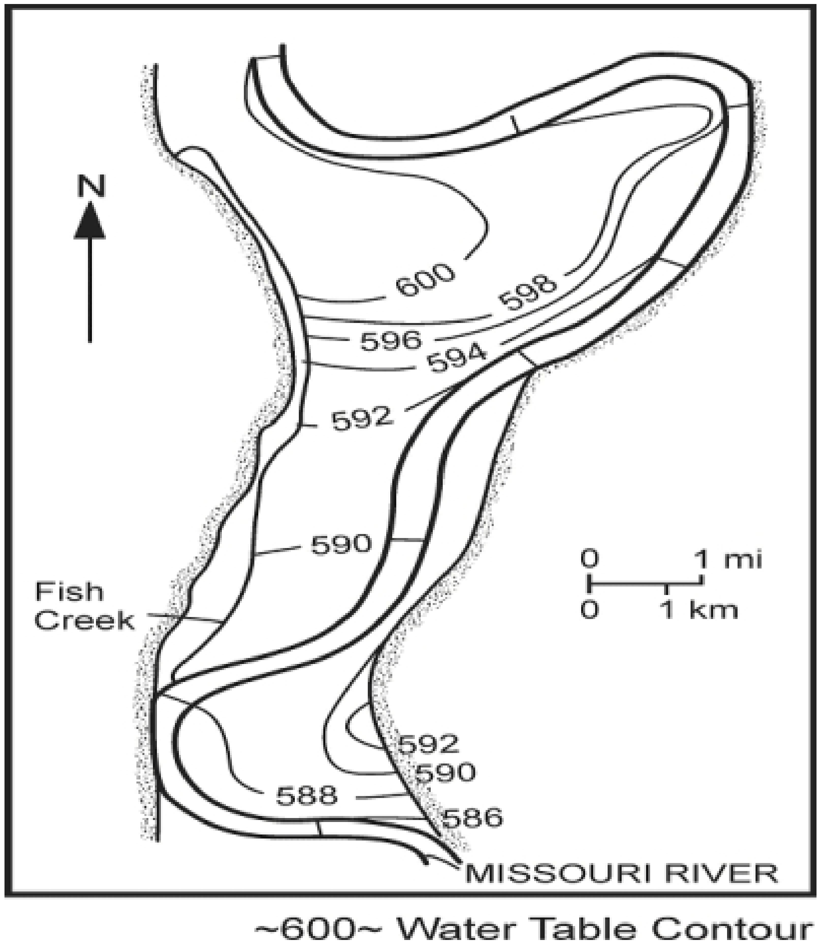

Figure 7. Mixed flow component: Lower Missouri River Alluvium, Missouri (Grannemann and Sharp, 1979).

The ability to detect and quantify patterns in groundwater – surface water interaction as nested spatial scales may be enhanced through the use of techniques complimentary to measurements using mini-piezometers. In particular, accretion studies of stream flow and thermal mapping can compliment the use of mini-piezometers and yield a more complete perspective on valley segment to reach scale patterns of groundwater-surface water interactions (Gordon, et al., 1992). This may involve the use of mini-piezometers at a high sampling resolution (Baxter and Hauer, 2000), fine scale measurement of streambed temperature (Gordon, et al., 1992), use of seepage meters (Lee and Cherry, 1978), digging sampling pits and performing dye injections (Dahm and Valett, 1996), or injection of conservative tracers (Gordon, et al., 1992). Any attempt to characterize patterns of groundwater-surface water interaction can benefit from a multi-scale approach, as well as the use of multiple, complimentary methods.

MECHANISMS OF GROUNDWATER DISCHARGE TO SURFACE WATER

Surface and subsurface water interactions occur by subsurface flow through the unsaturated soil and by infiltration into or exfiltration from the saturated zones. Also, in the case of karst or fractured terrain, interactions occur through flow in fracture or solution channels. In general, subsurface flow through porous media is sluggish. The mechanism(s) by which subsurface flow enters streams and contributes to the discharge response from individual rainstorm and snowmelt events is discussed in the literature (Winter, 1995). In particular, four mechanisms that account for fast subsurface contributions to the storm hydrograph have been identified: translatory flow, macropore flow, groundwater ridging, and return flow (Beaven, 1989).

Translatory flow, also known as plug flow or piston flow (Hewlett and Hibbert, 1967), is easily observed by allowing a soil column to drain to field capacity and then slowly adding a unit of water at the top. It would be observed that some water flows from the bottom immediately, but this is not the same water that was added at the top. Macropore flow rapidly moves through larger non-capillary soil pores (e.g. worm burrows, former root channels), resulting in rapid subsurface responses to storm events (Beven and Germann, 1982). Groundwater ridging describes large and rapid increases in hydraulic head that occur in groundwater during storm events (Sklash and Farvolden, 1979). As a result, the hydraulic gradient increases toward the stream and/or the size of the seepage face increases, thus enhancing fluxes to the stream. The groundwater discharge induced thereby may greatly exceed the quantity of water input that induced it. Return flow is the discharge of subsurface water to the surface. This may result if the water table and capillary fringe are close to the soil surface, such that small amounts of applied water are necessary to saturate the soil surface completely (Dunne and Black, 1970). The hydrological response of any particular watershed may be dominated by single mechanism or by a combination of mechanisms, depending on the magnitude of the storm event, the antecedent soil moisture conditions in the watershed, and/or the heterogeneity in soil hydraulic properties in the watershed (Sklash and Farvolden, 1979).

ESTIMATION OF GROUNDWATER FLUX IN THE HYPORHEIC ZONE

The flow of water on the surface and in the unsaturated and saturated zones is driven by gradients from high to low potentials. The hydraulic connection between the stream and groundwater may be direct, as shown in Figures 1 and 2. On the other hand, it may be disconnected by an intervening unsaturated zone, with streams losing water by seepage through a streambed down to a deep water table, as shown in Figure 3. The degree of connection can change over different reaches within any one stream and from time to time over the same reach.

For hydraulically connected stream-aquifer systems, the resulting exchange flow is a function of the difference between river stage and aquifer head. A simple approach to estimate flow is to consider the flow between the river and the aquifer to be controlled by the same mechanism as leakage through a semi-impervious stratum in one dimension (Rushton and Tomlinson, 1979). This mechanism, based on Darcy's law, where flow is a direct function of the hydraulic conductivity and head difference, can be expressed as:

$$Q = K \Delta h \tag{1}$$

where Q is flow between the river and the aquifer (positive for baseflow for gaining streams, and negative for river discharge for losing streams); $\Delta h = h_a - h_r$, (h_a is an aquifer head, and h_r is river head / stage); and K is a constant representing the streambed leakage coefficient (hydraulic conductivity of the semi-impervious streambed stratum divided by its thickness). Equation (1) can be used to represent both baseflow and river discharge, even though in practice the mechanisms representing the two processes can be different.

At times of high recharge, the leakage calculated by the linear relationship in equation (1) is much greater than would occur in practice and takes no account of water as its volume increases. For such increased resistance to flow a nonlinear relationship of the following form has been proposed (Rushton and Tomlinson, 1979):

$$Q = K_1 [1 - \exp(-K_2 \Delta h)] \quad (2)$$

where K_1 and K_2 are constants. In case where the suggestion of a maximum flow rate is not acceptable, a combination of linear and nonlinear relationships of the following form has been proposed (Rushton and Tomlinson, 1979):

$$Q = K_1 \Delta h + K_2 [1 - \exp(-K_3 \Delta h)] \quad (3)$$

where K_1 , K_2 and K_3 are constants.

In semiarid regions, where the water table is lower than the riverhead most of the time, an exponential relationship with a maximum flow is more appropriate. Under such conditions, channel seepage is often the largest source of recharge. The magnitude of infiltration depends on a variety of factors, such as hydraulic properties of the unsaturated zone, available storage volume in the unsaturated zone, channel geometry and wetted perimeter, flow duration and depth, antecedent soil water content, clogging layers on the channel bottom, and water temperature.

ECOLOGICAL SIGNIFICANCE

In regions where intense runoff occurs in a relatively short period of time, closed topographic depressions of varying sizes are filled by runoff to form ephemeral ponds or wetlands. Playas in arid and semiarid regions are some examples of such ephemeral ponds (Gordon et al., 1992; Brunke and Gonser, 1997). As the water level in a pond occupying a depression rises in response to input from overland flow and stream flow, water infiltrates from the pond to groundwater where the adjacent groundwater table is lower than the pond. The duration of standing water in the depression, called the hydroperiod, affects the species richness of aquatic invertebrates, amphibians, and their predators. From a study of 22 wetlands in various climatic regions, it has been found that amphibian species richness increases with increasing hydroperiod, but no significant relationship between species richness and wetland size has been found (Snodgrass, et al., 2000). In semiarid regions, intensive runoff coupled with high evapotranspiration produces wetlands with intermediate hydroperiods. This is crucial for biodiversity, because such wetlands maintain high productivity by periodic drying, which results in routine recycling of organic materials and nutrients (Gordon et al., 1992, Snodgrass et al., 2000).

The hyporheic zone, as shown in Figure 8, is a mixture of surface water and groundwater, and so physical and chemical characteristics are considerably different from stream water. The zone is therefore an ecotone between the surface environment characterized by light, high dissolved oxygen, and temperature fluctuation and the groundwater environment characterized by darkness, less oxygen, and stable temperature (Gilbert et al., 1994). Invertebrates living in the hyporheic zone exploit the groundwater environment to varying degrees. Some species spend their entire life cycle in the hyporheic zone, while others spend their egg and larval stage in the zone, and then move to the surface environment to spend their adult life. A third category of species uses the hyporheic zone only to seek protection from unfavorable situations (Gilbert et al., 1994). The food web of the hyporheic zone is fueled by the heterotrophic microbial communities that depend on dissolved oxygen provided by surface water exchange and particulate and dissolved organic carbon in nutrient rich groundwater. The microbes provide food for grazers, which in turn provide food for invertebrate predators. Dissolved organic carbon stored in hyporheic zone can serve as a food source when it is not readily available in surface water, and therefore the hyporheic zone has a crucial influence on the metabolism of the fluvial ecosystems (Brunke and Gonser, 1997).

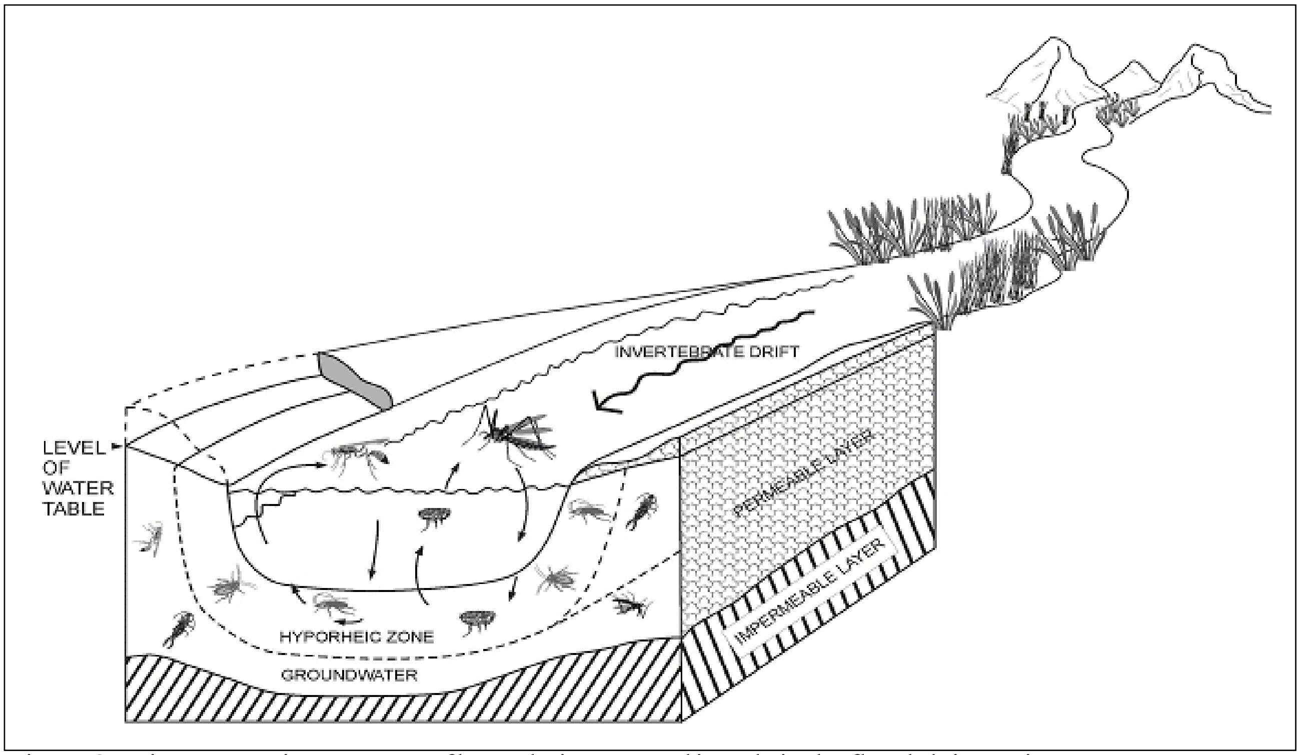

Figure 8. Diagrammatic summary of hyporheic zone and its role in the floodplain environment.

The hyporheic zone provides a number of ecologically important services. When surface water recharges groundwater, there is an opportunity for organic pollutants and detritus to become trapped in the sediment. The bacteria may then catalyze reactions that could change the chemicals into less toxic forms or into available nutrients. For instance, in contaminated aquifers many bacterial microorganisms residing in groundwater and sediment interstices can aid groundwater remediation by degradation and denitrification (Brunke and Gonser, 1997). During floods, excess water that enters bank storage may percolate downward to recharge groundwater or may re-emerge later at a different location in the watershed. During high flows, these mechanisms postpone the release of some of the water into streams to be delayed by days, weeks, or even months and thus partially reducing peak flood flows ((Brunke and Gonser, 1997). The interaction of groundwater with surface water within the hyporheic zone also has a thermal service. Since groundwater temperatures remain relatively constant, the water that discharges tends to be cooler than surface water in semiarid regions.

The hyporheic zone therefore serves as a thermal refuge for fish and other aquatic species in semiarid regions. The zone also serves as a habitat for microorganisms, macro-invertebrates, fish and wildlife; provides flow augmentation; refugia for endangered aquatic species under conditions of increased fragmentation and degradation of aquatic habitat; and food source for fish in surface water ecosystems and organic matter for microbial activity in groundwater ecosystems (Winter, 1995). Surface water moving into groundwater is one of the ways in which microorganisms may colonize groundwater environments. The presence or absence of certain groundwater species may indicate the location of groundwater surface water interaction zones and a decline in the diversity of groundwater species may indicate a decline in water quality (Gilbert et al., 1994). Groundwater invertebrates and microorganisms are an important food source for fish, and so the interaction of groundwater with surface water, which determines the availability of such organisms, has the potential to affect the viability of native fish populations (Gilbert et al., 1994).

ANTHROPOGENIC IMPACTS AND WATER RESOURCE SUSTAINABILITY

Floodplains in semiarid regions often serve as desirable areas for grazing and agriculture because of continuous availability of soil-water in the unsaturated zone and hence green pasture throughout the year. While these areas have the ability to introduce the cooling effects of groundwater to surface water and continuously make soil-water available in the unsaturated zone, they are also easily degraded by mismanagement. Grazing and agriculture may cause accelerated erosion and soil compaction in the valley bottoms, thus leading to permanent loss of such vital components of the ecosystem in semiarid regions (Gilbert et al., 1994).

In semiarid regions, crop production requires consumptive use of large quantities of water. Water, which is already scarce, must be shared among several consumptive as well as non-consumptive uses. Consequently, society faces serious water management problems in these areas. The decline of groundwater levels due to over-pumping ultimately results in reduced baseflow, which would otherwise have discharged into surface water to sustain aquatic life during low flows. At sufficiently large pumping rates, these declines induce flow out of the body of surface water into the aquifer, and this leads to stream flow depletion. The groundwater – surface water interaction is also important in situations of groundwater contamination by polluted surface water, and in situations of degradation of surface water by discharge of saline or other low quality groundwater. Information on groundwater – surface water interaction in semi – arid regions is therefore important for the sustainable management of water resources, both from a quantitative and qualitative perspective.

RESEARCH NEEDS

An understanding of the near-channel and in channel exchange of water, solutes, and energy is important for evaluating the ecological structure of stream systems and their management. Despite the recent increase in research on groundwater-surface water exchange, there are still many related processes that are not well understood. The relative importance of variables affecting the activity of the hyporheic zone at sediment and reach scales over time is unclear, and the spatial and temporal dynamics of groundwater discharge and recharge along active channels in varying geomorphic settings needs to be further investigated (Winter, 1995; Baird and Wilby, 1999). Whereas surface hyporheic exchanges and water residence times are known to be important regulators of subsurface biochemical transformations, the manner in which these parameters vary across streams and under different climatic conditions, such as semiarid regions, is not yet known (Jones and Holmes, 1996).

The effect of heterogeneity of water fluxes in general, and specifically between groundwater and surface water, is still a major challenge. The hydraulic properties of stream control the interactions between groundwater and surface water systems, but these properties are normally difficult to measure directly and vary spatially and temporally. The primary limitation has so far been the difficulty of spatially defining the hydraulic properties and heterogeneity of a stream. Streambed clogging and stream partial penetration are also important factors. All these factors need to be considered during analytical treatments of groundwater – surface water interactions (Jones and Holmes, 1996). Moreover, the relative importance of streambed clogging, stream partial penetration, and heterogeneity under semiarid conditions needs to be further investigated (Wassen and Grootjans, 1996).

Most techniques and models developed for groundwater-surface water interactions were based on information from humid regions (Winter, 1995). There is therefore a need to revise such techniques and models utilizing both in-situ and remote sensing observations from semiarid regions. These techniques also need to be coupled with Geographic Information Systems (GIS) technology and statistical analysis to study groundwater – surface water interactions in semi arid regions in a multidisciplinary and multi-scale approach (Bobba, 1996, Bobba et al., 2000).

SUMMARY AND CONCLUSIONS

Hydraulic, biochemical, thermal, and ecological conditions of groundwater and surface water influence the groundwater-to-surface water transition zone known as the hyporheic zone. The hyporheic zone is not static and may change as a result of daily or seasonal fluctuations in river stage and groundwater flow. Hyporheic zones range greatly in size and can be hundreds of meters deep and thousands of meters wide. The proportions of groundwater and surface water vary throughout the zones, and consequently, they differ in oxygen content, acidity, and temperature. The variability in physical and chemical characteristics will influence the local ecology within the zone. The functions of hyporheic zones also vary and may include providing sites for nutrient uptake, increasing water quality, and playing a role in the recovery of streams after storms.

The hyporheic zone may occur at the interface of the streambed with surface water or it may occur at depth within the streambed or banks. Surface water may enter the streambed at downwelling zones and reenter the river at upwelling zones. Downwelling generally occurs at the head of riffles, and upwelling (along with groundwater discharge) occurs at the upstream edge and base of pools. Anoxic conditions and anaerobic processes characterize the upward movement of groundwater in upwelling zones. High oxygen levels and aerobic processes characterize the downward movement of surface water in downwelling zones.

Hyporheic exchange, the process of water and solute movement across a streambed, varies with abrupt changes in the slope of a streambed or meanders in a stream channel. Depending on the type of sediment in the streambed and banks, the variability in the slope of streambed, and the hydraulic gradients in the adjacent groundwater system, the hyporheic zone can be as much as several meters in depth and hundreds of meters in width.

Within the hyporheic zone, ecological community structure varies with distance from the surface water. In general, invertebrate, protozoan, and bacterial populations decline with distance. The species diversity and community structure for invertebrates and protozoans also change with depth. The invertebrate species found in this ecotone include a mixture of species that spend part of their life cycle in the surface waters and a few specialized species that are found exclusively in groundwater. The macroinvertebrate species that reside within the hyporheic zone, including oligochaetes, isopods, and ostracods, have evolved special adaptations to survive in a habitat that is limited in food, oxygen, space, and light.

Knowledge and information on groundwater – surface water interaction at local, intermediate, and regional scales is essential not only for water resources management, but also for the sustainable management of ecosystems. Several examples have been presented in the literature on how exchange between groundwater and surface water affects interface ecology, and how biological communities affect the groundwater – surface water interaction under a range of environmental conditions. Studies investigating the advantages of the interaction have also been reported in the literature. However, there are still many gaps in our understanding of the processes involved in groundwater-surface water interaction, and the environmental implications of such interaction. The boundaries between hydrological and ecological research are gradually disappearing, yet a need remains for closer collaboration between these traditionally distinct disciplines and among researchers working in different climatic regions, so that research results may be pooled and applied to the benefit of the global environment, such as for the sustainable management and utilization of water resources.

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