Stream and Fluvial Plain Ground Water Interactions: Rescaling Hydrogeologic Thought

by William W. Woessner[a]

Abstract

Management of near-channel ground water and surface water to maintain stream health and floodplain ecological function requires hydrogeologists to refocus their conceptual models of water exchange between the aquifer and stream. The high hydraulic conductivity fluvial plain directs ground water flow down-plain where it exchanges with the stream channel creating gaining, losing, flow-through, and parallel-flow reaches. The resulting complex flow system requires consideration when profiles representing ground water flowpaths are constructed. In addition to interaction at the scale of the fluvial plain, exchange of ground water and surface water within and immediately adjacent to the stream channel creates hyporheic zones. The physical and biogeochemical extent of these zones depends on the head distribution and ground water flow directions, stream hydraulics, and channel bed conditions, and magnitudes and distributions of hydrogeologic parameters. Simulated conceptualizations of flow dynamics caused by slight increases in hydraulic potentials at the surface water-stream bed interface indicate stream-ground water mixing could occur to a depth of 1.7 m below the channel. Rescaling of traditional hydrogeologic approaches to include the fluvial plain and channel scale will result in opportunities to expand hydrogeologic research and participate in interdisciplinary research teams attempting to decipher and manage fluvial systems.

Introduction

Floodplains and associated channel systems should no longer be viewed by hydrogeologists as simply recharge or discharge zones for regional ground water systems (Winter et al. 1998; Woessner 1998). Instead, understanding how water within the fluvially derived sediments and the stream channel interacts is critical to efforts attempting to protect both the ground water and surface water resources, and the stream and riparian ecology (Valett et al. 1993; Dahm et al. 1998; Stanford 1998). The natural exchange of ground water and streams in these fluvial plain environments sustains the stream ecosystem. Meyer (1997) describes a healthy stream as having a "... sustainable and resilient ecological structure over time while continuing to meet societal needs and expectations."

Hydrogeologists rarely address stream health issues when assessing ground water systems within floodplain sediments. Instead, their work most often focuses on water rights and streamflow reduction (e.g., Walton 1970; Sophocleous et al. 1995; Conrad and Beljin 1996; Winter et al. 1998; Dickerman et al. 1997; Modica 1998). In the 1980s, when contaminant migration problems began to dominate ground water studies, fluvial systems were recognized as heterogeneous hydrogeologic settings containing preferential flow zones (e.g., Woessner et al. 1998; Rossi et al. 1994). Though contaminant transport efforts stressed the importance of fine-scale aquifer characterization, they were typically narrowly focused. Only recently have some hydrogeologists begun to investigate near-channel and in-channel exchange of water, a key to evaluating the ecological structure of stream systems (e.g., Valett et al. 1997; Harvey et al. 1996; Harvey and Bencala 1993; Wondzell and Swanson 1996; Castro and Hornberger 1991; Morrice et al. 1997; Wroblicky et al. 1998; Hendricks 1993; Palmer 1993). Such rescaling is critical as stream restoration and riparian management is proposed. By teaming with ecologists, a more comprehensive conceptual model of surface water and ground water interaction will result. These models will form a solid physical and geochemical foundation upon which stream health can be evaluated and stream remediation, if necessary, based. This work stresses the need for hydrogeologists to conceptualize surface water–ground water interaction at both the fluvial plain and channel scale.

The Fluvial Plain System

The fluvial plain can be thought of as a relatively planar feature containing the stream channel, floodplain, and associated flu-

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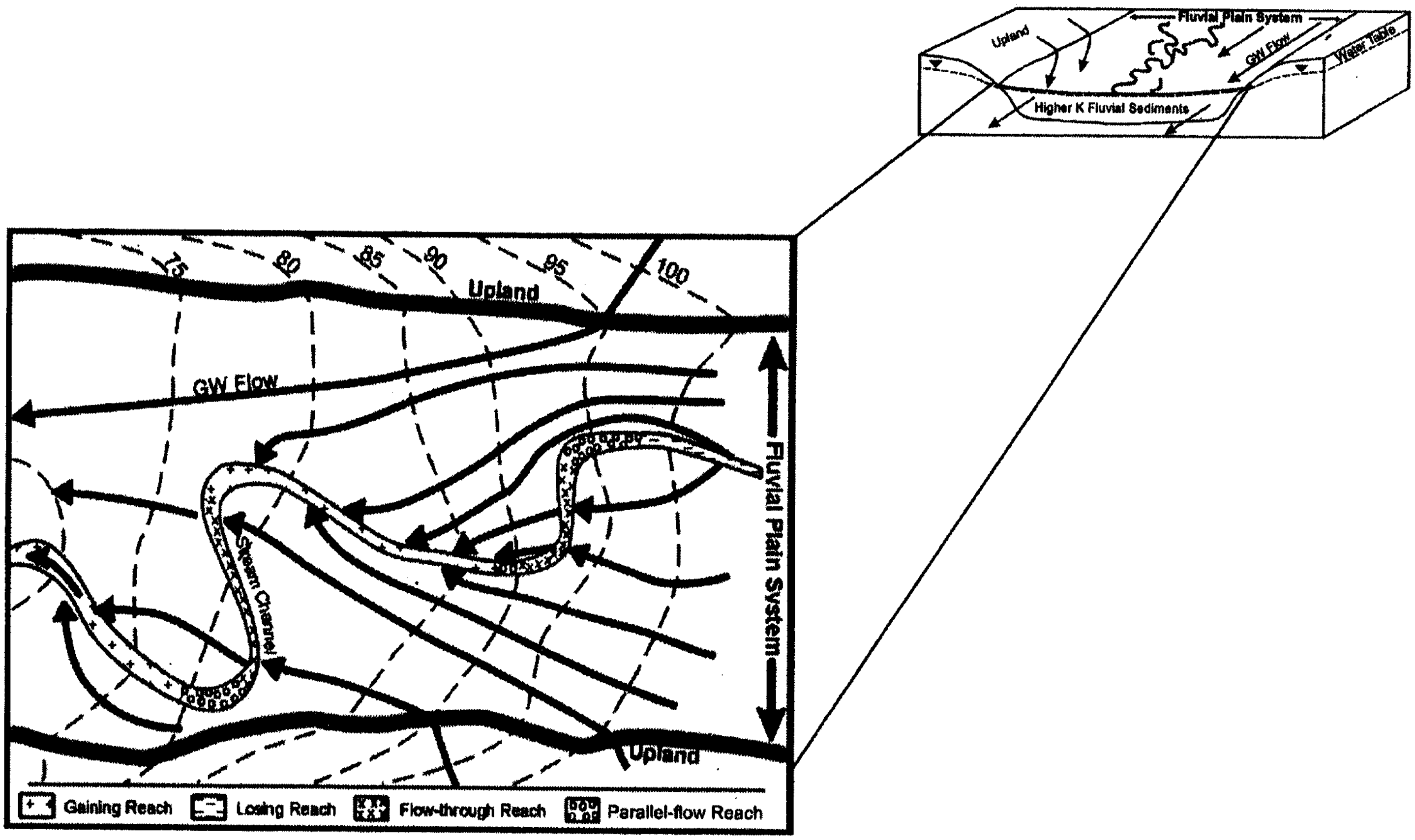

Figure 1. Ground water flow (arrows) from the upland into the higher hydraulic conductivity fluvial plain and a plan view of ground water flow in the fluvial plain. Equipotential lines are dashed and ground water–channel exchange indicated (modified from Woessner 1998).

vially derived sediments (Figure 1). The fluvial plain sediments are derived from riverine processes that are typically depositionally complex and generally higher in hydraulic conductivity than the adjacent uplands (Mullaney 1995; Woessner 1998). This hydrogeomorphic feature is termed a riverine valley by Winter et al. (1998) or an alluvial valley by others (e.g., Rosenshein 1988). The key to the fluvial plain designation is that it represents a zone of fluvially derived sediments from both ancient and current stream systems.

These deposits are stratigraphically complex, as they are created by stream systems ranging from meandering to braided (Miall 1996; Gross and Small 1998; Rosenshein 1988; Anderson 1989; Huggenberger et al. 1998). As a result, the distribution of permeable zones correlates with the depositional structure, which is generally orientated parallel to the axis of the plain (Winter et al. 1998, Rosenshein 1988; Sharp 1988). Riverine ecologists have also recognized this property, describing it as providing connectivity (Bencala 1993; Stanford and Ward 1993).

Fluvial plain ground water systems flow down-plain with depositional structure, slope, and relatively higher hydraulic conductivity of the sediments controlling transport conditions (Figure 1). Such flow occurs within plains having widths of a few tens of meters (e.g., Wroblicky et al. 1998; Castro and Hornberger 1991; Wondzell and Swanson 1996; Harvey and Bencala 1993) to kilometers (e.g., Rosenshein 1988; Sharp 1988; McMurtrey et al. 1959).

Relation of Stream Stage and Channel Orientation to Ground Water Exchange in the Fluvial Plain

The flow, transport, and exchange of ground water, nutrients, carbon, and oxygen in the fluvial plain is controlled by (1) the distribution and magnitude of hydraulic conductivities both within the channel and the associated fluvial plain sediments (Wroblicky et al. 1998; Dahm et al. 1998; Woods 1980; Winter et al. 1998; Holmes et al. 1994); (2) the relation of stream stage to the adjacent ground water gradients; and (3) the geometry and position of the stream channel within the fluvial plain. Characterization of the exchange of ground water with a river typically is accomplished by (1) measuring water levels in wells, piezometers, and piezometer nests installed within the fluvial plain, on the banks of the channel, and within the streambed (Triska et al. 1989; Modica 1998; Lee and Cherry 1978; Henry et al. 1994; Wroblicky et al. 1994; Wondzell and Swanson 1996); (2) performing stream gauging at a number of

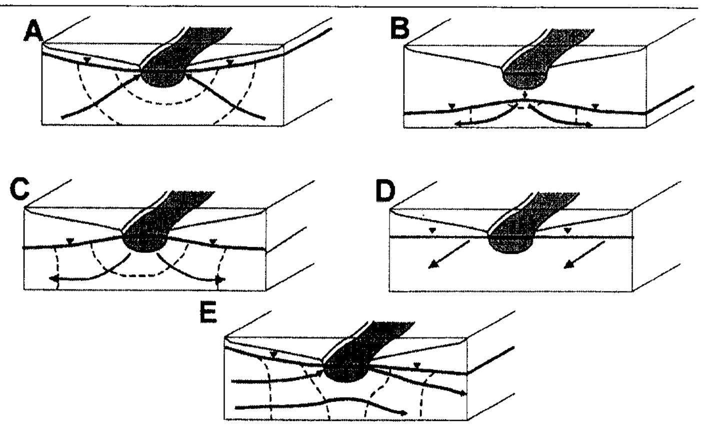

Figure 2. Fluvial plain–ground water and stream channel interactions showing channel cross sections classified as: (a) gaining; (b) and (c) losing; (d) parallel-flow; (e) flow-through. The stream is shaded. The water table and stream stage (thicker lines), ground water flow (arrows), and equipotential lines (dashed) are shown. Cross sections A, B, C, and E are constructed parallel to ground water flow; D is perpendicular to ground water flow (modified from Woessner 1998).

stream cross sections over a short time period (synoptic survey) and comparing discharge measurements (Buchanan and Somers 1969); (3) comparing ground water and stream geochemistry (Benner et al. 1995; Rutherford and Hynes 1987; DeWalle and Pionke 1989; Brunke et al. 1998; Hoehn and von Gunten 1989); and (4) conducting one-dimensional stream channel tracer studies (Bencala et al. 1983; Bencala and Walters 1983; Bencala 1984; Bencala et al. 1990; Harvey et al. 1996; Choi et al. 1998; Dietrick et al. 1989; Jakeman et al. 1989; Runkel 1998; Runkel et al. 1998).

Results of these efforts allow description of stream reaches as gaining, losing, flow-through, and parallel-flow (Woessner 1998; Winter et al. 1998; Hoehn 1998) (Figures 1 and 2). Ground water enters the stream channel forming gaining river reaches when the three-dimensional ground water head at the stream channel interface is greater than the stream stage (Figure 2a). Conversely, losing stream reaches are found in channel sections where the stream stage is greater than the underlying and adjacent ground water head (Figures 2b and 2c). When the channel stage is less than the ground water head on one bank and is greater than the head at the opposite bank, a flow-through channel forms (Figure 2e). A fourth condition, termed a parallel-flow channel, occurs when the channel stage and ground water head are equal (Figure 2d). This type of channel was previously termed a "zero exchange channel" (Woessner 1998). However, though both ground water and stream flow would be essentially parallel, on a smaller scale some limited exchange between the stream and its bed may occur.

When the stream channel is generally orientated parallel to the fluvial plain, gaining, losing, and parallel-flow channels are most likely to occur. Flow-through reaches are most often found when a channel cuts perpendicular to the fluvial plain ground water flow field (Wroblicky et al. 1998; Woessner 1998; Hoehn 1998; Huggenberger et al. 1998).

Using the conceptual flow and exchange models presented herein, the construction of fluvial plain and stream cross sections

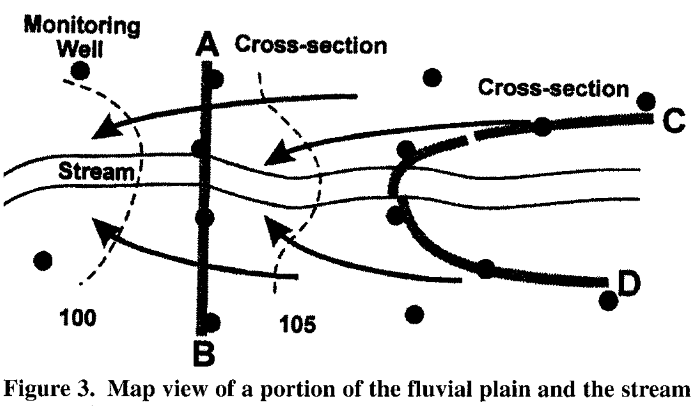

Figure 3. Map view of a portion of the fluvial plain and the stream channel instrumented with monitoring wells (black dots). Cross section C-D is located along a flowline where A-B is not.

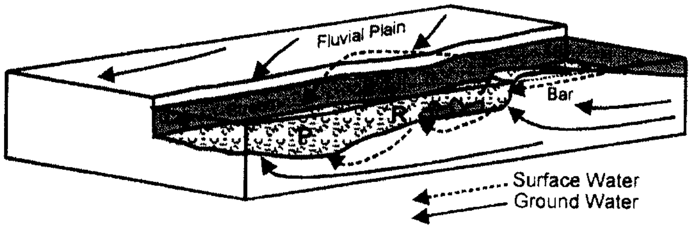

Figure 4. Near-channel fluvial plain and stream channel showing ground water and surface water exchange. R and P indicate a riffle and pool sequence, respectively.

to show ground water flow and quality along a flowpath to the stream requires careful consideration (e.g., Harvey and Bencala 1993; Wondzell and Swanson 1996). Figure 3 illustrates the proper location of wells (cross section C-D) to accomplish these purposes for a section of gaining stream. Cross section A-B may be used to illustrate the geology, however, within the proposed fluvial plain flow system, it is not parallel to a flow line. Proper conceptualization (Figure 1) and measurement of the flow field in the near-channel area will result in appropriate locations of hydrogeologic cross sections.

The Hyporheic Zone

Stream and riparian ecologists have cited the importance of stream-ground water mixing and refer to the zone in which this occurs as the hyporheic zone (e.g., Williams and Haynes 1974; Triska et al. 1989; Valett et al. 1990; Hendricks and White 1991; Grimm and Fisher 1984; Bencala 1984; Stanford and Ward 1988; Winter et al. 1998). Unfortunately, a single definition for the hyporheic zone has not been adapted by the biological, physical, and geochemical researchers (White 1993). Valett et al. (1993) suggest the hyporheic zone is ". . . the subsurface region of streams and rivers that exchanges water with the surface." However, to the hydrogeologist, this would include most all of the shallow ground water system as its endpoint is often a stream. From a physical and geochemical viewpoint, the hyporheic zone can be thought of as a portion of the saturated zone in which surface water and ground water mix. Physical, geochemical, or biological evidence of the intermixing of the two systems is used to characterize a hyporheic zone (Triska et al. 1989).

Relation of Stream Channel Geometry to Ground Water Exchange

Mixing of surface water and ground water takes place within the near-channel sediments. Such near-channel exchange occurs at many scales, from centimeters to tens of meters depending on bed geometry and hydraulic-potential strengths (Bencala 1984; Savant et al. 1987; Thiobodeaux and Boyle 1987; Valett et al. 1992; Harvey and Bencala 1993; White 1993; Pusch 1996; Vervier et al. 1992; Bencala and Walters 1983; Hendricks and White 1991; Winter et al. 1998) (Figure 4). Research has examined pressure potential differences at the stream bed caused by positive relief such as bars, ripples, dunes, and boulders (Savant et al. 1987; Jobson and Carey 1989). Work has also focused on the pool and riffle sequences found in many high gradient streams (Hendricks 1993; Harvey and Bencala 1993). This work found surface water enters channel sediments at the heads of riffles and exits at the riffle base in pools. Stream water may also circulate out of the stream channel as water enters the riffles and flows through the adjacent banks and back into the downgradient pool (Winter et al. 1998; Harvey and Bencala 1993; Wroblicky et al. 1998; Wondzell and Swanson 1996; Morrice et al. 1997; Harvey et al. 1996). Most researchers stress the importance of sediment heterogeneity and head distribution in producing intricate exchange patterns.

The nature of the exchange between a section of channel can be partially assessed by installing mini-piezometers in the streambed, and observing head and water quality differences between the ground water and surface water (Lee and Cherry 1978; Henry et al. 1994; Benner et al. 1995; Hendricks and White 1991). Temperature surveys have also been used to examine bed exchange process (Silliman et al. 1995). Sometimes these physical measurements are

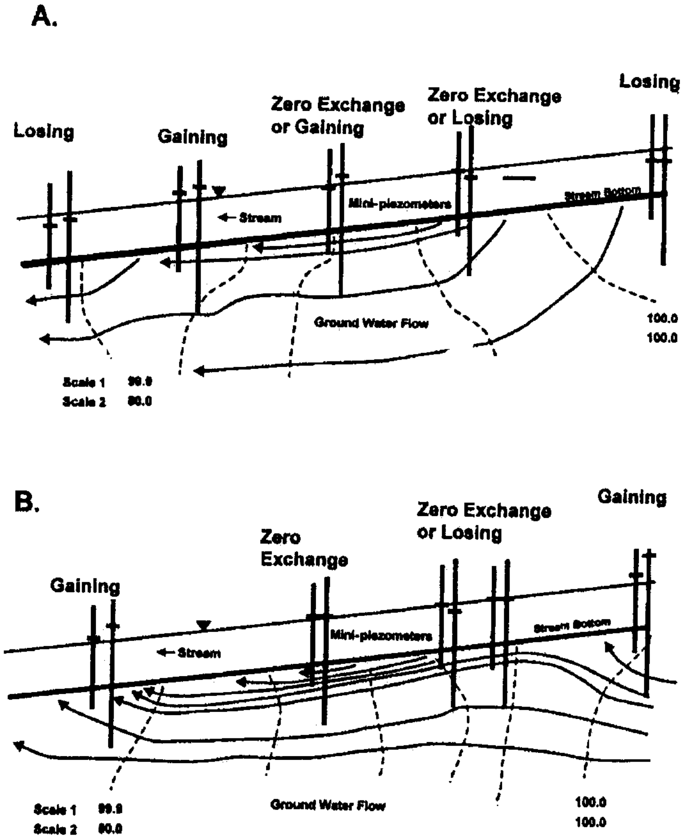

Figure 5. Cross sections within the stream channel parallel to the channel slope. Section A represents a losing channel reach within which local exchange of hyporheic water occurs. Section B represents a gaining channel reach within which flow of surface water into the channel sediments occurs. Scale values indicate such exchanges can occur at a multiple of scales. Vertical lines indicate the position of open-ended mini-piezometers and horizontal bars show the water level in the tube.

difficult to interpret, as what appear to be contradictory positive, negative, or neutral head differences are obtained over adjacent portions of the stream channel. It should be realized that the stream bed topography and the corresponding water exchange can cause localized flow systems within the beds of overall gaining and losing stream reaches (Figures 5a and 5b). Piezometers alone may not assess these fine scale flow systems.

Simulation of Channel-Bed Scale Exchange

A profile-section flow and transport model illustrates the scale and complexities water exchange within hyporheic zones. The 10 m by 3 m profile model generically represents a sand or sand and gravel dominated stream bed section (Figure 6). The top boundary represents the stream-bed interface where surface water infiltrates over the right one-half and ground water discharges across the left portion. Ground water flow enters the right-hand boundary with a small upward component of flow. Bottom and left boundaries are no-flow. The hydraulic conductivity is assumed to be anisotropic, $K_x = 100$ m/d and $K_z = 10$ m/d.

The finite-difference flow and solute transport model uses 50 columns and 30 rows, 1500 cells each 0.2 m by 0.1 m (MODFLOW [McDonald and Harbaugh 1988], MODPATH [Pollock 1994] and MT3D96 [Zheng 1996] as formulated in VisualMODFLOW [Waterloo Hydrogeologic Inc. 1997]). The specified head boundary along the top increases linearly from left to right, 99.8 m to 100 m. The right vertical boundary is assigned specified head values of 100 m at the top right cell and 100.02 m at the bottom cell. Head values at cells in between are linearly interpolated. After a steady-state head solution was obtained, a specified concentration of 100 mg/L was introduced along the right one-half of the top boundary to represent a conservative solute. Model longitudinal dispersivity of 1 m and transverse vertical dispersivity of 0.01 m represent sediment dispersive properties of sand and gravel. Ground water has a concentration of 0 mg/L.

The distribution of surface water occurring under the described conditions is obtained for the modeled stream profile (Figure 6a).

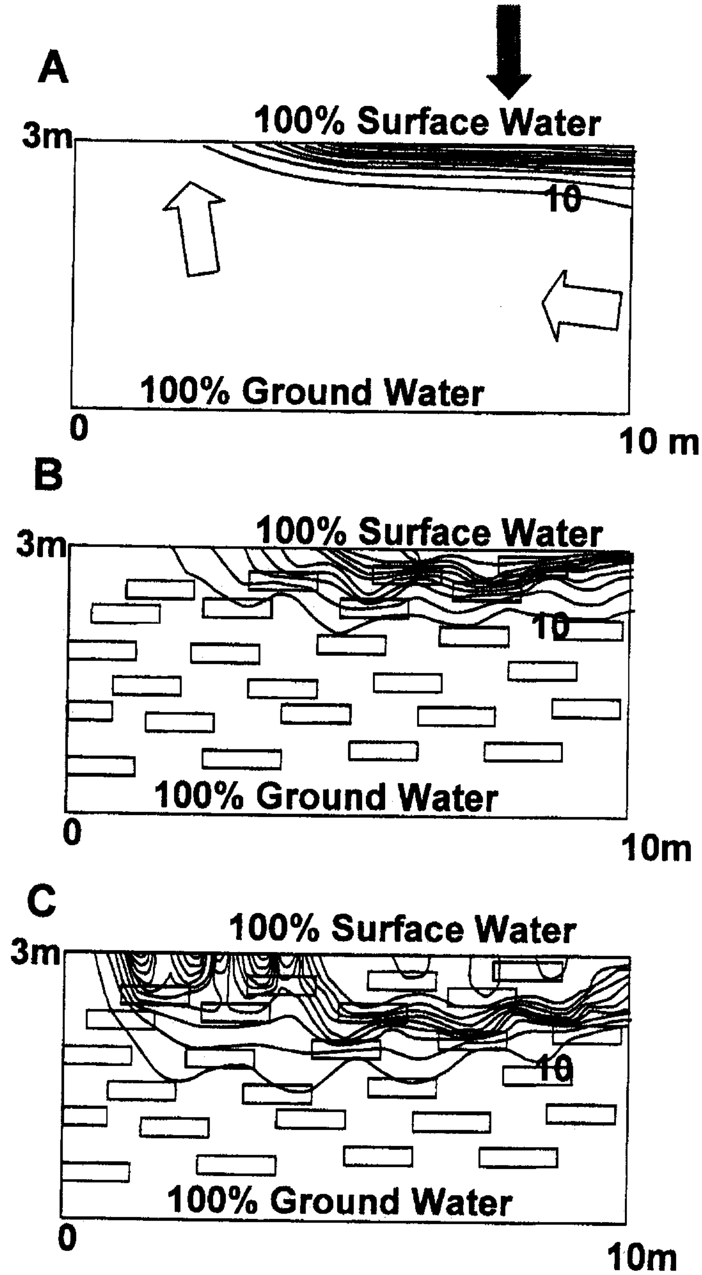

Figure 6. Profiles of the stream channel sediments. Contour interval for all plots represent 10% changes in the mixed composition of the ground water. The 10 contour represents where 10% of the downward infiltrating surface water has mixed with 90% of the ground water. (a) Surface water infiltrates over right one-half of the top boundary (gray arrow) and ground water enters the left boundary and exits along the left one-half of the top boundary (white arrows). (b) Same conditions as A, except rectangles representing zones with 10 times higher hydraulic conductivity values. (c) Same conditions as (b) with the addition of 0.02 m increases in specified head in evenly spaced 0.20 m sections at 0.8 m intervals across the top boundary.

A second steady-state simulation was run using zones of higher hydraulic conductivity (10 times higher than the original setting) as represented by a number of horizontal rectangles (Figure 6b). A third steady-state flow and transport simulation illustrates a further complexity, slight increases in head (0.02 m) at 0.2 m long segments evenly spaced at 0.8 m intervals from left to right across the top boundary. These conditions were used to examine possible effects of bed topography on the hyporheic zone configuration (Figure 6c).

Modeling results show the mixing zone for river water extends about 0.7 m into the underlying fluvial sediment under initial homogeneous anisotropic conditions (Figure 6a). When horizontal zones of higher hydraulic conductivity are added, the mixing zone exceeds 1 m and becomes more internally complex (Figure 6b). The third simulation reveals a more irregular 10% mixing zone contour extending 1.5 m into the ground water system. Results show the presence of small local surface water dominated cells in both the surface water infiltration zone (right top boundary) and in the ground water discharge zone. Based on modeling results, it is clear the study of flow and chemistry of the near-channel hyporheic zone requires development of a complex conceptual model. Measuring parameters within this exchange region is challenging, as fine-scale characterization is necessary, but few tools are available.

Placing Stream Health Within the Fluvial Plain Hydrogeologic Framework

The concept of stream health as proposed by Meyer (1997) focused on maintaining an ecological structure. This structure leads to discussions of stream, riparian, and fluvial plain function. Basically, streams are not only end and beginning points of ground water flow and water supply systems, they are critical components of the riparian and riverine ecology. In the interest of fully characterizing this ecosystem, hydrogeologists should work with multidisciplinary researchers evaluating stream and riparian function. Fishery biologists have recognized the importance of ground water discharge to streams in terms of spawning location and success (e.g., Hansen 1975). However, stream and fishery biologists attempting to reclaim a stream or restore fisheries have little or no guidance as to the percentage of ground water–surface water exchange per kilometer that is desirable to reestablish. Researchers attempting to redesign channels to restore or enhance the bed exchange mechanisms again have only a limited template to assist them. Although we realize that nutrient cycling in the hyporheic zone is a key component to stream function, comparison studies of natural and impacted stream reaches under varied stream-fluvial plain settings have not been done.

A recent workshop sponsored by the U.S. Environmental Protection Agency (EPA) (Workshop on Surface-Water Ground-Water Interaction, Denver, January 1999) recognized that, if not already occurring, the potential for contaminated ground water from hazardous waste sites to impact surface water systems (especially the hyporheic zones) is high at many sites. Though this workgroup recognized the importance of the near stream exchange processes to riverine ecology, it found only scattered studies that had identified and quantified impacts.

It is clear that a concerted effort is needed to develop databases for natural and impacted stream—ground water exchange. In addition to basic hydrogeologic evaluations, new and innovative geochemical and biological tools need to be brought to bear (such as the tracer methods described by Harvey et al. [1996]). Interdisciplinary research groups should form to develop a comprehensive understanding of the processes occurring and controlling the exchange of water at the fluvial plain and near-channel scale (Palmer 1993).

Summary

Conceptualizing hydrogeologic conditions at the fluvial plain scale reveals a complex interaction between streams and ground water systems. Ground water flow is generally parallel to the higher hydraulic conductivity fluvially derived plain. Exchange of ground water with the stream occurs by discharge, recharge, and flow-through. Zones with common heads are termed parallel-flow reaches. The general down-plain nature of ground water flow needs to be considered when hydrogeologic cross sections are constructed. Exchange of surface water and ground water also occurs at the channel-bed scale. Local, shallow surface water circulation into the underlying sediments creates areas of ground water recharge and discharge within zones generally characterized as gaining or losing stream sections. These hyporheic zones are also influenced by heterogeneities in the sediment hydraulic conductivity distribution and the topography of the streambed. This paper attempts to emphasize the importance of conceptualizing and characterizing stream-ground water exchange at the fluvial plain and channel scale. Important work has begun to determine the magnitude, location, and seasonal variability of these interactions. Fortunately, opportunities to contribute to this area of research exist. An important next step is to document the exchange processes in larger stream-fluvial plain systems over multiple geomorphic and climatic conditions.

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