groundwater

Influence of Oscillating Flow on Hyporheic Zone Development

by Herb S. Maier[1] and Ken W.F. Howard[2]

Abstract

The hyporheic zone is an ecologically important ecotone that describes the extent to which nutrient-rich surface waters penetrate the shallow subsurface adjacent to a flowing surface water body. Although steady-state models satisfactorily explain the incursion of surface water into the subsurface as a function of head gradients developed across streambed riffles, they fail to account for the depth that surface water is observed to penetrate the subsurface or for the extent to which the hyporheic zone develops adjacent to the stream channel. To investigate these issues, transient flow modeling has been conducted at the riffle scale and supported by data for an instrumented site in northern Ontario where stream-stage fluctuations are strictly regulated. Model results show that daily stream-stage fluctuations between 0.6 and 4 m produce oscillating solute flow paths that typically reduce residence times of water and solutes in the hyporheic zone from 60 days or more under steady-state conditions to less than 1 day. Furthermore, similar stream-stage fluctuations increase the depth that solutes pervade the subsurface and banks lateral to the stream from around 1 m under steady-state conditions to as much as 2 and 10 m, respectively. The results demonstrate that the transient flow conditions triggered in the subsurface by variable stream stage can exert a strong influence on hyporheic zone development and have important implications for the hyporheos. The results are especially important for hyporheic communities that may survive gradual changes to their living conditions by migrating to more hospitable aquatic habitats, but are unable to respond to rapid changes provoked by more extreme hydrological events.

Introduction

The hyporheic zone is an ecologically significant ecotone that can be characterized in physical, chemical, and biological terms by the temporally dynamic subsurface mixing of surface water and groundwater beneath and lateral to a stream channel (Bencala 2000; Woessner 2000; Runkel et al. 2003; Howard et al. 2006). In this research, the hyporheic zone is defined in physiochemical terms by the subsurface presence of at least 10% advected stream water (Triska et al. 1989). This definition is useful as it provides a method to delineate the hyporheic zone and permits quantitative assessments to be made regarding the size, extent, and amount of surface water/groundwater mixing within the hyporheic zone. As surface waters tend to be rich in nutrients such as nitrate, ammonium, phosphate, and dissolved organic carbon (Sophocleous 2002), the hyporheic zone is able to support an important group of diagnostic organisms commonly referred to as hyporheos (Fraser and Williams 1998).

Given the importance of hyporheic biotic activity, much research has been carried out in recent decades to understand hyporheic zone flow dynamics. In early flume studies, Thibodeaux and Boyle (1987) and Elliott and Brooks (1997) showed that exchange flows between the stream and streambed are commonly associated with streambed undulations (e.g., pool-riffle sequences) that

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generate head gradients within the streambed sediments to drive subsurface flow. Water enters the upstream face of the bedform and generally leaves the streambed on the downstream face. The process has been further supported by more recent flume studies by Packman et al. (2004) and confirmed under field conditions by Storey et al. (2003) who also replicated the subsurface flow mechanism using a series of steady-state groundwater flow models. Hyporheic zones may also develop lateral to the streambed either due to large-scale head differences across stream channel meanders (Cardenas 2009) or due to short-term inflow into the stream bank during periods of elevated stream stage (e.g., Howard et al. 2006). In all cases, the hydraulic conductivity of streambed sediments and the stream water velocity have been shown to have an important influence on hyporheic interactions (Lautz and Siegel 2006).

To date, much of the research has considered only steady-state flow conditions. Such studies have helped explain how surface water penetrates the subsurface but often fail to account for the depth of hyporheic activity and provide a somewhat simplistic representation of true water particle behavior, real residence times, and the mechanisms by which groundwater and surface water mix.

In this study, we use transient groundwater flow modeling supported by field data from Northern Ontario, Canada, to explore the extent to which temporal variations in stream-stage influence subsurface flow dynamics. Although previous attempts have been made to describe the temporal variability of the hyporheic zone, the majority of this work has involved transient storage models that consider solute transport and retention times in pool-riffle sequences and meandering type streams (Hantush et al. 2002; Wörman et al. 2002; Lin and Medina 2003; Schmid 2003; Ensign and Doyle 2005; Gooseff et al. 2005; Kazezyilmaz-Alhan and Medina 2006; Cardenas 2009). More recent studies have begun to investigate the role of variable flows on the physical and chemical aspects of surface water and groundwater exchange (Hatch et al. 2006, 2010; Malcolm et al. 2006; Krause et al. 2007; Gu et al. 2008; Nyberg et al. 2008; Käser et al. 2009). However, no attempts have been made to investigate the effect of variable stream stage and resulting transient flow behavior on the temporal development of the hyporheic zone and on solute flow paths.

In our work, we perform short-term transient flow simulations of hyporheic zone behavior using MODFLOW (Harbaugh et al. 2000) coupled with MODPATH (Pollock 1994) and MT3D (Zheng 1990) to demonstrate how the temporal variability of stream-stage affects:

- The size and extent of the hyporheic zone
- The flow paths followed by particles/solutes
- Particle/solute residence times.

It is expected that the results of this work will aid in the development of stream assessment tools that can minimize the impacts of fluctuating stream stage on the hyporheos. For example, like all living organisms, hyporheic organisms exhibit a range of physiochemical conditions necessary for their survival. Coupled with the knowledge of the hyporheos' tolerance to changes in physiochemical conditions, groundwater flow and transport modeling can then be used as a tool to test whether proposed water management actions such as dam operation would cause hyporheic residence time to be less than that required by hyporheic biota. This approach may be used in streams that are subject to relatively rapid changes in streamflow conditions such as regulated streams for the generation of hydroelectric power.

Methods

Field Site and Field Data

To support the research investigation, a field site was established on the Magpie River near Wawa, Ontario, Canada (Figure 1). The Magpie River lies within the Lake

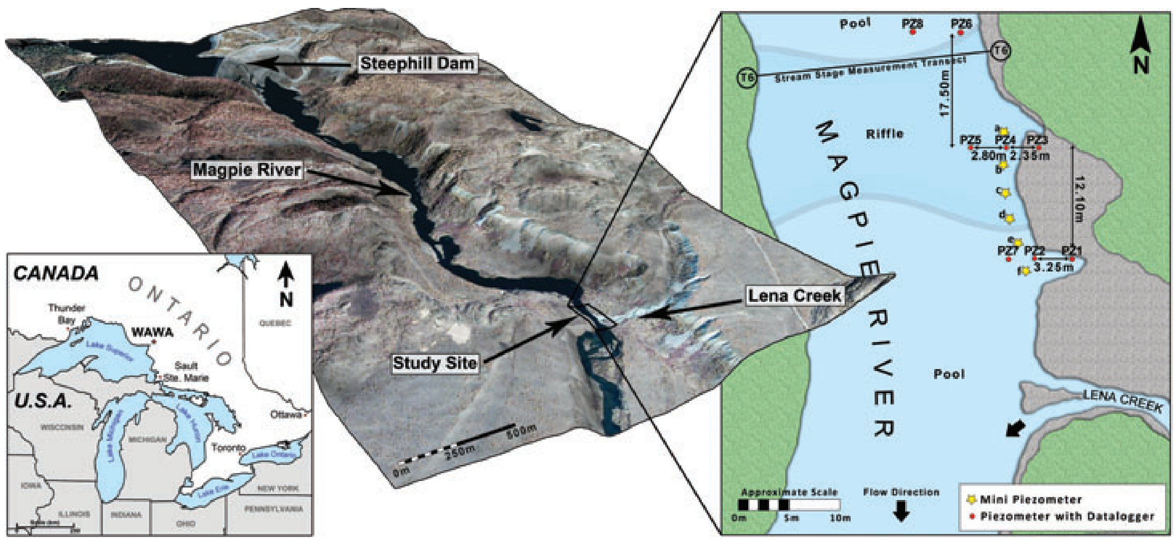

Figure 1. Site location and instrumentation.

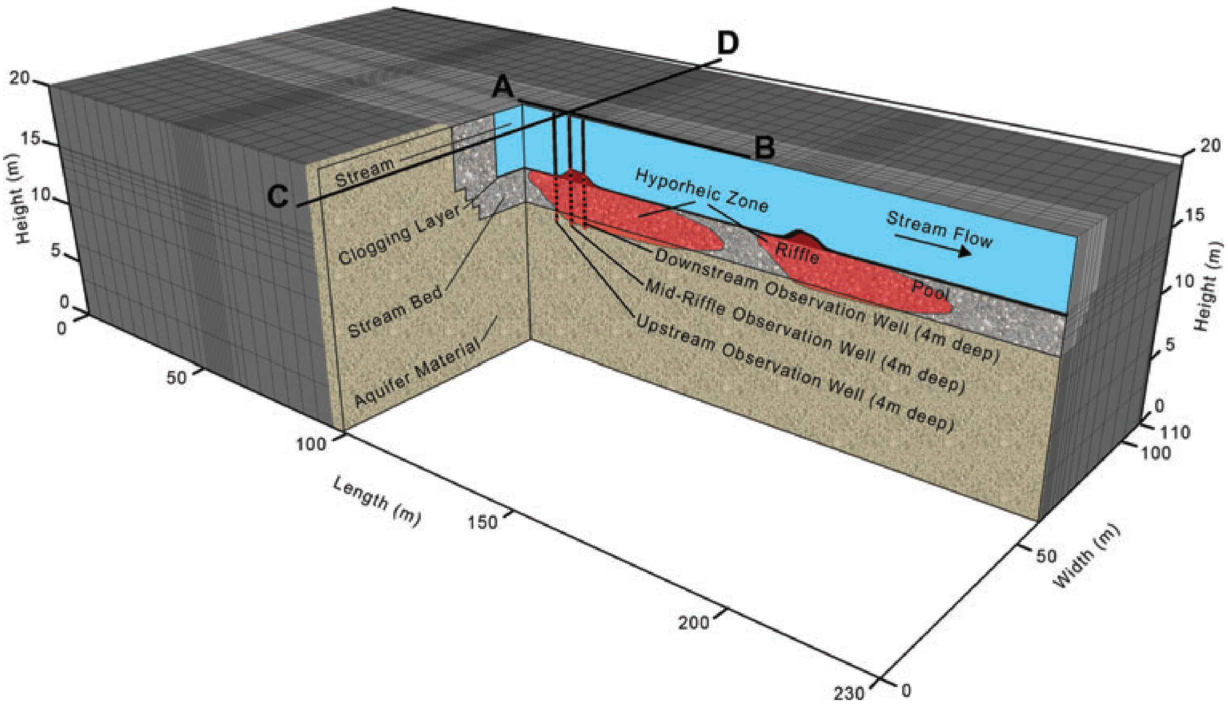

Figure 2. Three-dimensional cross section of the model domain showing the upstream, middle, and downstream riffle locations of model observation wells (3× vertical exaggeration). Cross sections AB and CD are referred to in Figures 7 and 8.

Superior watershed and is regulated by three hydroelectric dams. All the three dams are located upstream of the study site, but only the Steephill Falls hydroelectric power generating facility, located approximately 2 km upstream, directly influences stream stage at the site. The release of water from the dam increases flow in the river, a process referred to as "ramping" and creates a steady rise in stream stage. Typically, the stream stage is maintained at an elevated level for between 3 and 12 h in every 24-h period. The field site (Figure 1) consisted of eight piezometers permanently installed to various depths (0.6-1.0 m) beneath the streambed, across and upstream of a near-shore riffle about 12-m long, and six temporary minipiezometers located along the center-line of the riffle and penetrating to a depth of 0.3 m. The depths of the piezometers are reported as the depth to the bottom of the screened interval. Each permanent piezometer was perforated over the bottom 0.25 m of its length with approximately 30 evenly-spaced holes and equipped with a pressure transducer that provided head measurements at 3-min intervals. Monitoring took place over two 4-month periods in 2004 and 2005, each from June until October. Stream-stage measurements at 15-min intervals were provided for the same periods by the Watershed Science Centre at Trent University in Ontario, Canada.

Groundwater Flow Model

To investigate the effects of variable stream stage on the hyporheic zone, a generalized transient three-dimensional (3D) numerical groundwater flow and transport model was developed using MODFLOW (Visual Modflow Pro v4.1 software by Waterloo Hydrogeologic Inc.) to reproduce the basic subriffle flow behavior demonstrated by the field data. The 3D model domain is shown in Figure 2. The model was 230 m in length, 110 m wide, and 20 m deep and included a 10-m wide stream channel with a mean gradient of 0.0026, consistent with the mean channel gradient of the Magpie River. The stream channel contained three riffles each 10 m in length and 1 m high at its crest and it was assumed that the riffles extended across the full width of the stream channel. The riffles were separated by pools 50 m in length, a spacing consistent with the general study area and the work of Thompson (2001). The horizontal grid size varied across the model from 7 × 5 m at a distance of approximately 50 m from either side of the stream channel, to 1 × 1 m where riffles were present. In pools between the riffles and within approximately 10 m of the stream channel, the grid size was stepped and ranged from 1 × 1 m to a maximum size of 5 × 1 m.

Vertically, the model comprised 10 variably-spaced layers to represent the three hydrogeologically distinct zones known to be present at the site:

1. A thin, 0.2-m thick semi-pervious clogging layer separating the stream channel from the streambed sediments.
2. Streambed sediments, ranging in thickness from 3 m between riffles and up to 4 m beneath the riffle crests, comprising cobbles and gravels that extend outward approximately 10 m on either side of the stream channel.
3. Surrounding aquifer material comprising sand and gravel.

Table 1
Hydrologic Parameters Used in the MODFLOW Simulations

Parameter	Value
Model domain	230 × 110 × 20 m
Hydraulic conductivity K (streambed sediments: clogging layer)	1.8×10^{-4} m/s
Hydraulic conductivity K (streambed sediments: cobble and gravel)	9×10^{-4} m/s
Hydraulic conductivity K (aquifer material: sand and gravel)	1×10^{-7} m/s
Sediment anisotropy (K_h/K_v)	10
Sediment porosity (n)	0.30
Aquifer recharge (R)	200 mm/year
Stream channel gradient	0.0026

The layers ranged in thickness from approximately 3 m at the bottom of the model domain to 0.2 m for the clogging layer. The clogging layer was introduced to represent the top few centimeters of the streambed which commonly exhibits a lower hydraulic conductivity than underlying sediments due to the settling and straining of suspended and bedload sediments (Saenger et al. 2002; Blaschke et al. 2003). This layer was assigned a hydraulic conductivity one-fifth that of the streambed sediments (Schälchli 1992). Table 1 provides a summary of the hydrologic parameters used in the model simulations.

The stream (i.e., stream stage) was represented in the model using spatially and temporally variable constant head boundaries assigned to the uppermost layer of the model. The stream was assigned the same average linear gradient as the stream channel (0.0026), declining from 16.2 m at the upstream end of the model to 15.6 m at the downstream end. This initial stream stage corresponds to an initial stream depth of 1.2 m. To represent the influence of pressure head variations along the streambed surface caused by streambed topography (pool-riffle sequences in this case) and to generate flows across the three riffles, stream channel constant heads were elevated by 0.01 m on the upstream side of each riffle and decreased by the same amount on the downstream side. When the resulting head difference is added to the head difference associated with the sloping channel, it produces a total head difference of about 0.05 m across each riffle. This value is consistent with the flume studies of Thibodeaux and Boyle (1987) and Elliott and Brooks (1997) and with field observations made in the temporary piezometers at the Magpie River field site.

Model boundaries remote from the river were represented by general head boundaries assigned to generate an initial hydraulic gradient of 0.009 in the direction of the stream channel, a value that was consistent both with the field data and a steady-state catchment-scale finite element model described in Howard et al. (2006) that was developed for the broader study area. To achieve a hydraulic gradient of 0.009, it was necessary for boundary heads to range from 16.45 m on the left (upstream) side of the model domain to 16.05 m on the right (downstream) end of the model domain. Recognizing that general head boundaries are dependent on model-generated heads and flows, the appropriate head conditions were achieved by assigning general head boundaries that varied linearly between 17.4 and 16.9 m.

Solute Transport Modeling

To simulate the influx and subsequent behavior of stream-derived water in the subsurface, the MT3D and MODPATH modules were used. For convenience, it was assumed that the Magpie River could be considered as a constant concentration source of a nonreactive, conservative solute. Although this approach is appropriate for investigating the extent of hyporheic zone development, it may not provide a realistic indication of subsurface penetration and residence times for dissolved components that are reactive and exhibit significant retardation factors.

MT3D was used to investigate the relationship between fluctuating water stage and the extent of hyporheic zone development. For modeling purposes, the solute concentration was assumed to be 10 mg/L in the stream water and 0 mg/L in the groundwater. Recognizing that the hyporheic zone can generally be defined by the subsurface presence of at least 10% advected stream channel water (Triska et al. 1989), the boundary of this zone was represented by the 1 mg/L isosurface. To present the results of the simulations, model observation wells were installed on the upstream end of the riffle, in the middle of the riffle, and on the downstream face of the riffle, each with monitoring points positioned every 0.5 m to a depth of 4 m (Figure 2). Solute concentrations were predicted at 0.6-h intervals to show temporal changes in solute concentration and to produce vertical profiles of solute concentration.

To predict the nutrient/solute flow paths and residence times within the streambed for nonreactive constituents, the MODPATH particle tracking module was used. Particles were added to each of the 10 grid cells contained on a longitudinal section centered along each riffle and also to each grid cell contained on longitudinal sections located along the banks of the stream channel where the riffles were present. As each of the three riffles included three longitudinal sections each with 10 grid cells, the process involved the release and tracking of 90 particles. For presentation purposes only a handful of these particles, which portray key-riffle flow behavior, are included in the model results discussed in the following sections.

Transient Model Runs

Model simulations were performed for six different stream-stage scenarios. The first scenario represented natural, undisturbed conditions with a steady water depth of 1.2 m. This scenario was chosen as a baseline of comparison for subsequent simulations. This model was run for steady-state groundwater flow with the solute transport modules being continued until all the released particles re-emerged in the stream (for MODPATH) or chemical steady state was achieved (for MT3D). For the subsequent five scenarios (daily stream-stage fluctuations of 0.6, 0.8, 2, 3, and 4 m), the model was run in transient mode for a period of 20 days. Stream-stage fluctuations of 0.6, 0.8, and 2 m were chosen to simulate stream-stage fluctuations that may be expected in a regulated stream. The larger stream-stage fluctuations of 3 and 4 m were simulated to provide an "upper bound" to this study. During each 24-h period, the stream stage was increased linearly for 6 h, maintained at a steady level for 6 h, decreased linearly for 6 h, and finally maintained at the original stream stage for the remaining 6 h. For example, in the 0.8 m daily stream-stage fluctuation scenario, stream stage would increase linearly from the original depth of 1.2 to 2.0 m during the first 6-h period, remain at a depth of 2.0 m for the next 6 h, decrease linearly from a depth of 2.0 m back to the initial depth of 1.2 m during the next 6 h, and then maintained at the original depth of 1.2 m for the remaining 6 h. Each 6-h interval consisted of 10 time steps to provide a total of 40 time steps for each daily cycle of stream-stage fluctuation.

Results

Results of the Field Observations

The effects of the change in stream stage are demonstrated by the data set shown in Figure 3a for Piezometer PZ5 for the period June 24, 2005 to July 13, 2005. During this period, ramping raises and lowers the stream stage by approximately 0.6 m each day and generates a head response within the streambed of between 0.1 and 0.3 m. Importantly, the range of stream-stage values "envelopes" the streambed heads such that there is a period within each ramping cycle (Figure 4) when groundwater heads exceed stream heads, i.e., upwelling occurs, and there is a period in which the head gradient is the reverse and downwelling occurs. In effect, a complex temporal flow regime is created with water particles and nutrients occasionally reversing flow directions.

Results of the MODFLOW Simulations

The results of the MODFLOW simulation are shown in Figure 3b for a model piezometer located at a depth of 1 m beneath the streambed on the downflow side of the center riffle. They show the head response to observed daily stream-stage fluctuations of up to 0.6 m over a 20-day period. Comparison of Figure 3b with field data for a similar location in Figure 3a shows that the processes occurring in the field are well represented in the model. This includes the small range of groundwater head variation as compared to the variation in stream stage and the daily reversal in head gradient that generates cycles of upwelling and downwelling. A time series representing vertical head gradients for observed and simulated stream stage and groundwater heads is shown in Figure 3c. The primary difference between the field and model data is the range of the groundwater head variation, which tends to be slightly larger in the model and corresponds to slightly smaller simulated vertical gradients. Model-generated groundwater heads also tend to increase slightly each day in an asymptotic manner which is likely attributed to the model attempting to reach equilibrium in response to the simulated stream-stage fluctuation regime. In addition, the field data show a slightly delayed groundwater head response to changes in stream stage of approximately 0.2 h at Piezometer PZ5 at a depth of 1 m (Figure 4). The model also produces a similar delayed response, but is approximately one order of magnitude shorter than the field data. These differences may be attributed to a number of factors, but likely reflect the inability of the model to represent the 3D complexities of the Magpie River riffle. For the purposes of this research, this is not considered to be a problem as it was never the intention to build a model that could fully replicate transient head conditions at the study site. Instead the objective was to produce a transient flow model that could adequately reproduce key subriffle behavior such as head gradient reversals, and this was achieved.

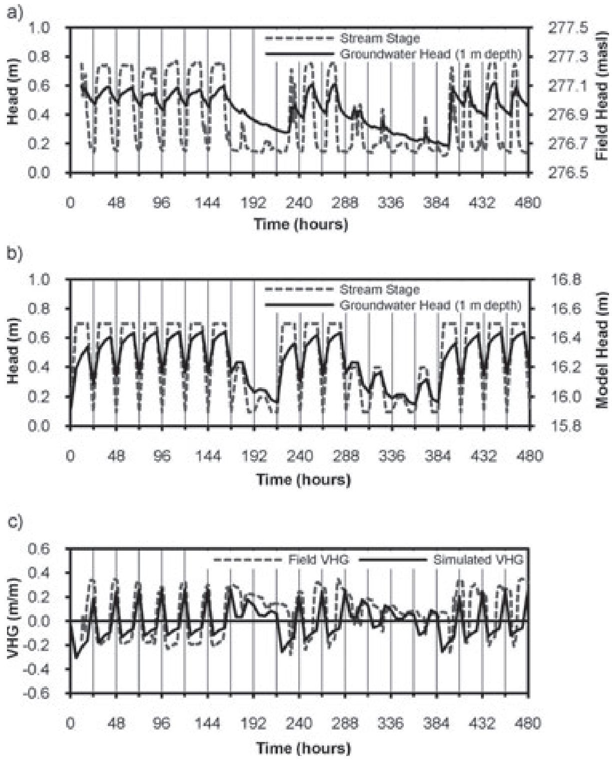

Figure 3. (a) Observed stream stage and groundwater head response at Piezometer PZ5 situated at a depth of 1 m beneath the riffle. Data are shown for a period of 20 days between June 24, 2005 and July 13, 2005 (actual measured heads are displayed in the secondary y-axis). (b) Simulated head response to observed daily stream-stage fluctuations of up to 0.6 m for a model piezometer located at a depth of 1 m beneath the center riffle (actual model heads are displayed in the secondary y-axis). (c) Comparison of vertical head gradients between stream stage and groundwater head at a depth of 1 m beneath the center of the riffle for observed and simulated data.

Figure 5a shows the effects of increasing the magnitude of stream-stage fluctuation. It shows how simulated

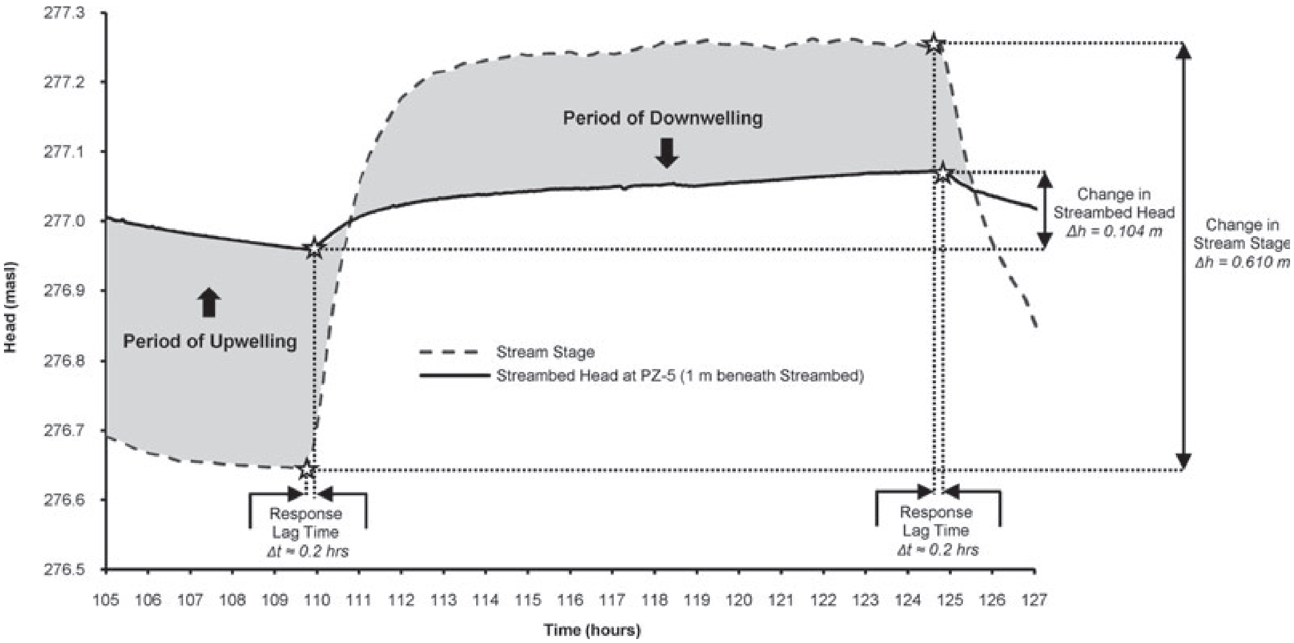

Figure 4. Details of the field data at Piezometer PZ5 shown in Figure 3a for a 22-h period. Under naturally steady conditions upwelling occurs at this location with groundwater head slightly higher than the stream stage. Ramping results in a reversal of the hydraulic gradient and promotes periods of significant downwelling. The location of PZ5 is shown in Figure 1.

groundwater heads respond to stream-stage fluctuations of 0.8, 2, 3, and 4 at a depth of 1 m beneath the streambed on the downflow side of the center riffle during the final 3 days of each 20-day simulation period. Figure 5b illustrates the intervals of upwelling and downwelling for the last 3 days of the 3-m stream-stage fluctuation scenario. All simulations have intervals of upwelling and downwelling, and the magnitudes of the groundwater head response are such that the gradients of flow (and reversals of flow) increase in proportion to the magnitude of the stream-stage fluctuation. This is illustrated in Figure 5 which shows the maximum head difference generated for two situations:

- When stream stage is at its peak and downwelling occurs the difference between stream stage and groundwater head is less pronounced.
- When stream stage has returned to normal flow conditions (15.9 m) and upwelling is restored the difference between stream stage and groundwater head is more pronounced.

In the first situation, the maximum head difference between stream stage at its peak and the mean groundwater head at a depth of 1 m on the downflow side of the center riffle is 0.19 m (in a downwards direction) for a stream-stage fluctuation of 0.8 m. The magnitude of this difference increases to 0.45 m for stream-stage fluctuations of 2 m and eventually to 0.82 m for stream-stage fluctuations of 4 m. In effect, a fourfold increase in the magnitude of the stream-stage fluctuation leads to a fourfold increase in the magnitude of the head difference. In the second situation, when stream stage returns to normal, the increase in groundwater head is only 0.55 m higher

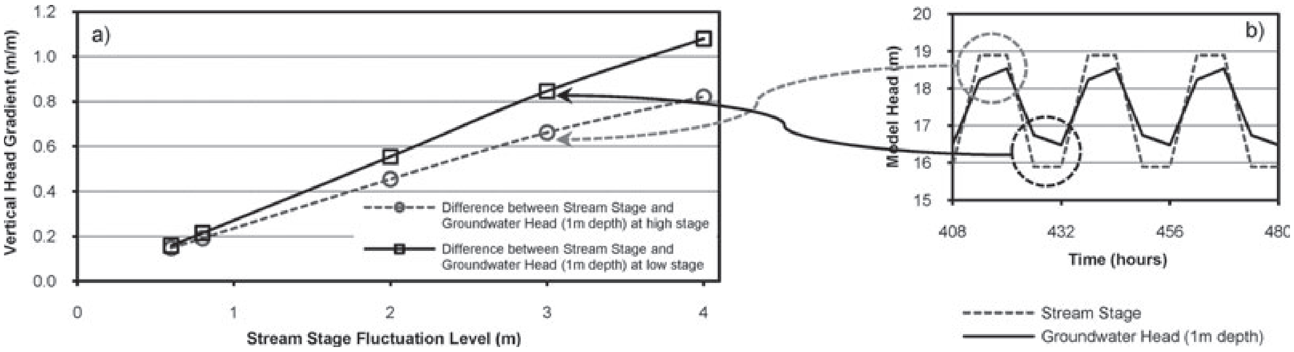

Figure 5. (a) Simulated head difference between stream stage and groundwater (1 m depth) during periods of maximum upwelling and maximum downwelling. (b) Example of the simulated head response over a 3-day period for the 3-m daily stream-stage fluctuation scenario illustrating the head differences between stream stage and groundwater (1 m depth).

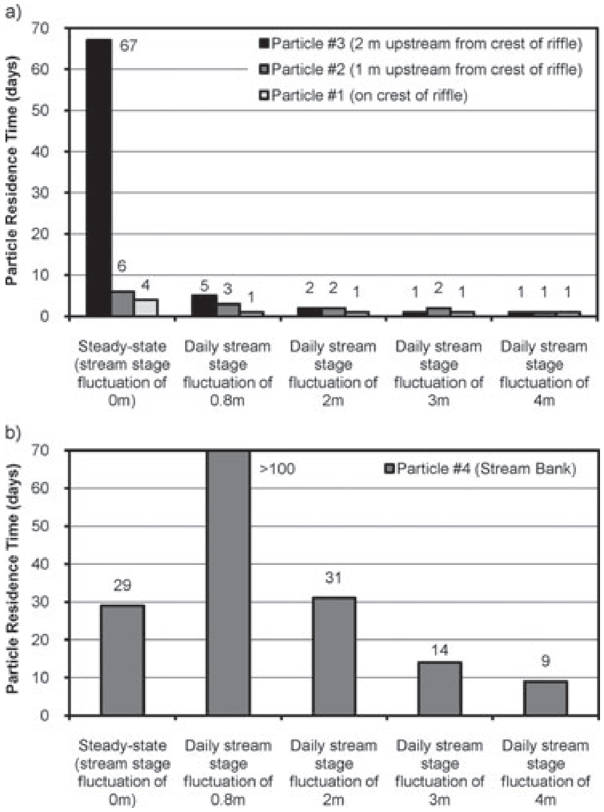

Figure 6. Comparison of subsurface residence times for selected particles as a function of daily stream-stage fluctuation. (a) Residence time for three particles released in the center of the stream channel along the riffle. (b) Residence time for a particle released upstream of the riffle along the stream bank.

than the original stream-stage level. For stream-stage fluctuations of 3 and 4 m, the average groundwater heads are 0.85 and 1.08 m higher than the original stream-stage levels. The amount of downwelling produced during periods of elevated stream stage, however, does not change as significantly as the amount of upwelling during periods of low stream stage over the varying magnitudes of stream-stage fluctuation. The amount of downwelling increases only slightly as the magnitude of stream-stage fluctuation increases. For stream-stage fluctuations of 0.8 m, the elevated stream stage is only 0.19 m higher than the groundwater head. For stream-stage fluctuations of 4 m, the elevated stream stage increases to only 0.82 m higher than the groundwater head. This has important implications for both the size of the hyporheic zone and the solute/nutrient flow paths within the streambed as shown by the MODPATH and MT3D results in the following sections.

Influence of Stream-Stage Fluctuation on Flow Paths and Particle Residence Times

Stream-stage fluctuations were found to have a major impact on flow paths and particle residence times. The results are summarized in Figures 6, 7, and 8. In Figure 8, the flow paths predicted by MODPATH for the simulation period are shown by solid black wavy lines (gently curving black lines for the steady-state condition in Figure 8a and 8b). The color-shaded proportion of stream water profiles shown as background were determined through MT3D simulations and represent the percentage of stream-derived water within the streambed and banks when daily stream stage is at its peak.

Particle residence time refers to the time it takes for a particle to complete its journey through the subsurface. Particles that enter the streambed near the crest of the riffle tend to return to the stream channel relatively quickly, whereas particles that enter the streambed on the upstream face of the riffle or close to the streambank will tend to experience longer residence times.

Particle residence times for four representative particles are shown in Figure 6 for five stream-stage scenarios: steady-state and stream-stage fluctuations of 0.8, 2, 3, and 4 m. Figure 6a shows the residence times for three particles released in the center of the stream channel, the first on the riffle crest, the second 1 m upstream of the riffle crest, and the third 2 m upstream of the riffle crest, whereas Figure 6b shows the residence times for a particle released upstream of the riffle crest along the streambank. Under steady-state conditions, particle residence times range between 4 and 67 days for particles released beneath the center of the channel and approximately 29 days for the particle released along the streambank. Under classical understanding, a subsequent rise in stream stage would be expected to suppress rates of groundwater flow to the stream and increase the depth to which nutrient-rich stream waters penetrate the subsurface. As a result, particle residence times would intuitively increase. Although such an interpretation may be valid for a permanent rise in stream stage, model results suggest that a fluctuating stream stage can significantly reduce particle residence times, particularly for particles that enter the riffle along the center of the stream channel. As shown in Figure 6a, a 0.8-m fluctuation of stream stage reduces particle residence time to between 1 and 5 days and a 4-m fluctuation of stream stage reduces particle residence time to just 1 day.

For a particle released along the stream bank, the response is more complicated. Elevating the stream stage forces particles into bank storage as shown in Figure 7b. When stream stage lowers, the water stored in the bank eventually returns to the stream, as shown in Figure 7c. However this may take some time as, initially at least, some of this flow continues in the direction away from the stream. Model results shown in Figure 6b reveal that a 0.8-m fluctuation of stream stage generates a particle residence time of over 100 days. As the magnitude of the stream-stage fluctuation increases, particle residence times within the stream bank reduce to as little as 9 days for a daily stream-stage fluctuation of 4 m.

Figure 8 shows the path lines followed by selected particles. Under steady-state conditions, particles entering the upstream face of a riffle follow smooth flow lines to their exit on the downstream face of the riffle or subsequent trough or pool (Figure 8a and 8b). However, under transient conditions where daily fluctuations

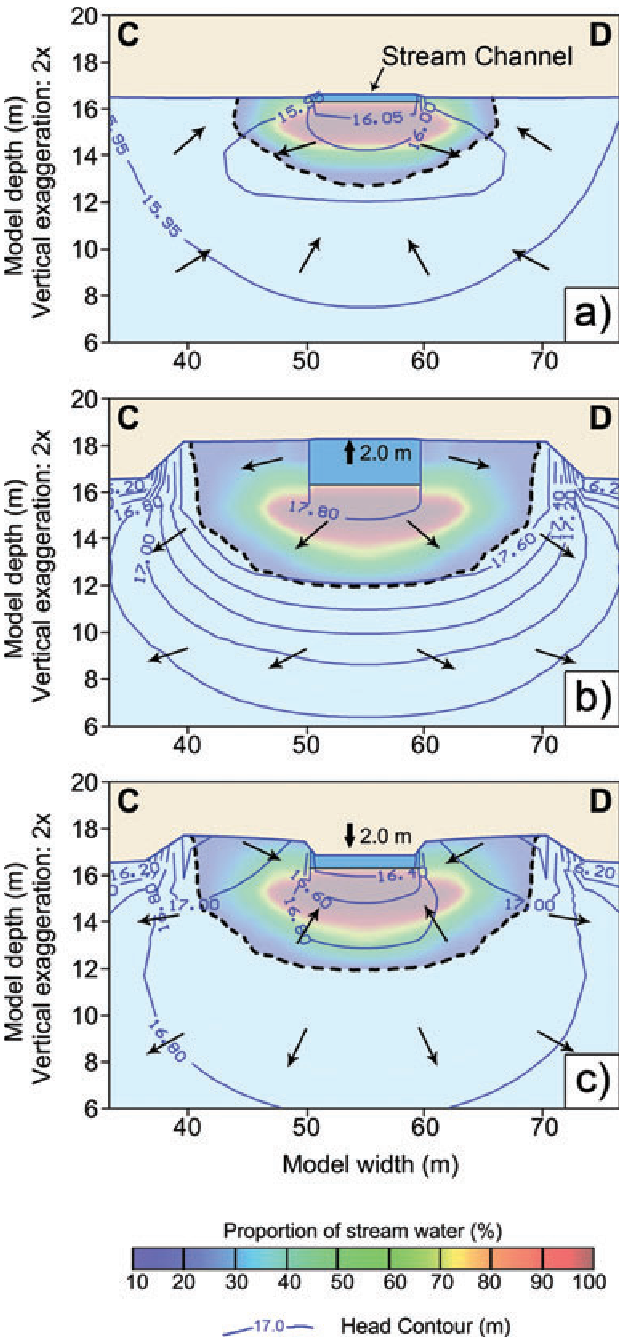

Figure 7. The processes by which daily fluctuations in stream change create and release water from bank storage (example for the 2-m daily stream-stage fluctuation scenario). (a) Prior to a 2-m rise in stream stage. (b) During the peak of a 2-m rise in stream stage. (c) After a subsequent 2-m decline in stream stage. The color-shaded proportion of stream water profiles shown as background represents the proportion of stream water within the streambed and banks and were determined through MT3D simulations. The arrows indicate flow directions and the location of cross section CD is shown in Figure 2.

of stream stage are introduced (Figure 8c, 8e, and 8g), the particles respond with an oscillatory motion that leads to their premature reintroduction into the stream channel. This behavior is somewhat analogous to the process that occurs when a surge block is used to wash out unwanted sediment that accumulates in the screen, gravel pack, and aquifer matrix during the construction of a well (Misstear et al. 2006). Stream water is forced into the riffle during the period of high water stage and extracted just as rapidly when stream stage is reduced and head gradients are reversed.

A similar behavior is exhibited by particles that leave the stream to enter bank storage (Figure 8d, 8f, and 8h). Here, however, particle path lines and residence times are influenced both by heads beneath the stream and by the local water table (Figure 7). For relatively small stream-stage fluctuations (e.g., 0.8 m shown in Figure 8d), the particle follows a long, gently arching, albeit oscillatory path that is broadly similar in overall direction to that followed by the particle under steady-state conditions (Figure 8b). However, as the magnitude of the stream-stage fluctuation increases, the amplitude of the oscillatory motion experienced by the particle also increases and the curvature of the arching path intensifies (Figure 8f and 8h). It is the sharp streamward curvature of the path line that returns the particle to the stream prematurely.

Figure 9 shows the amplitude of the particle oscillation as a function of stream-stage fluctuation. Particles moving within the banks adjacent to the stream experience a greater range of oscillatory motion than particles moving via the streambed riffle, and this is believed to reflect strong competition between the near-shore water table to "capture" stream bank particles. For example, daily stream-stage fluctuations of 0.8 m generate approximately between 1.75 and 2.5 m of particle movement into and out of the stream bank, while particle movement within the riffle is confined to a vertical distance of only 1.25 to 1.5 m. For daily stream-stage fluctuations of 4 m, particle oscillation extends as much as 7 m into the stream bank while vertical particle movement within the riffle shows only a moderate increase to between 3 and 3.5 m.

Influence of Stream-Stage Fluctuation on Groundwater/Surface Water Mixing

Detailed results of the MT3D simulations are summarized in Figures 10, 11, and 12. They demonstrate how fluctuating stream stage influences the size of the hyporheic zone and the proportion of surface water present.

Under steady-state flow conditions (no variations in stream stage), the hyporheic zone, as defined by the subsurface presence of at least 10% advected stream channel water (Triska et al. 1989), has a volume of approximately 676 m^3 (Figure 10). However, when daily stream-stage fluctuations of between 0.8 and 4 m are introduced, the volume of the hyporheic zone effectively doubles. It also varies in volume during the daily stream-stage cycle, with elevated stream stage causing a volumetric increase of between 5% and 10% when compared to the volume at the low stream stage of the cycle. Significantly, the magnitude of the daily stream-stage fluctuations appears to have little effect on hyporheic zone volume with comparable results observed for all four transient scenarios shown in Figure 10.

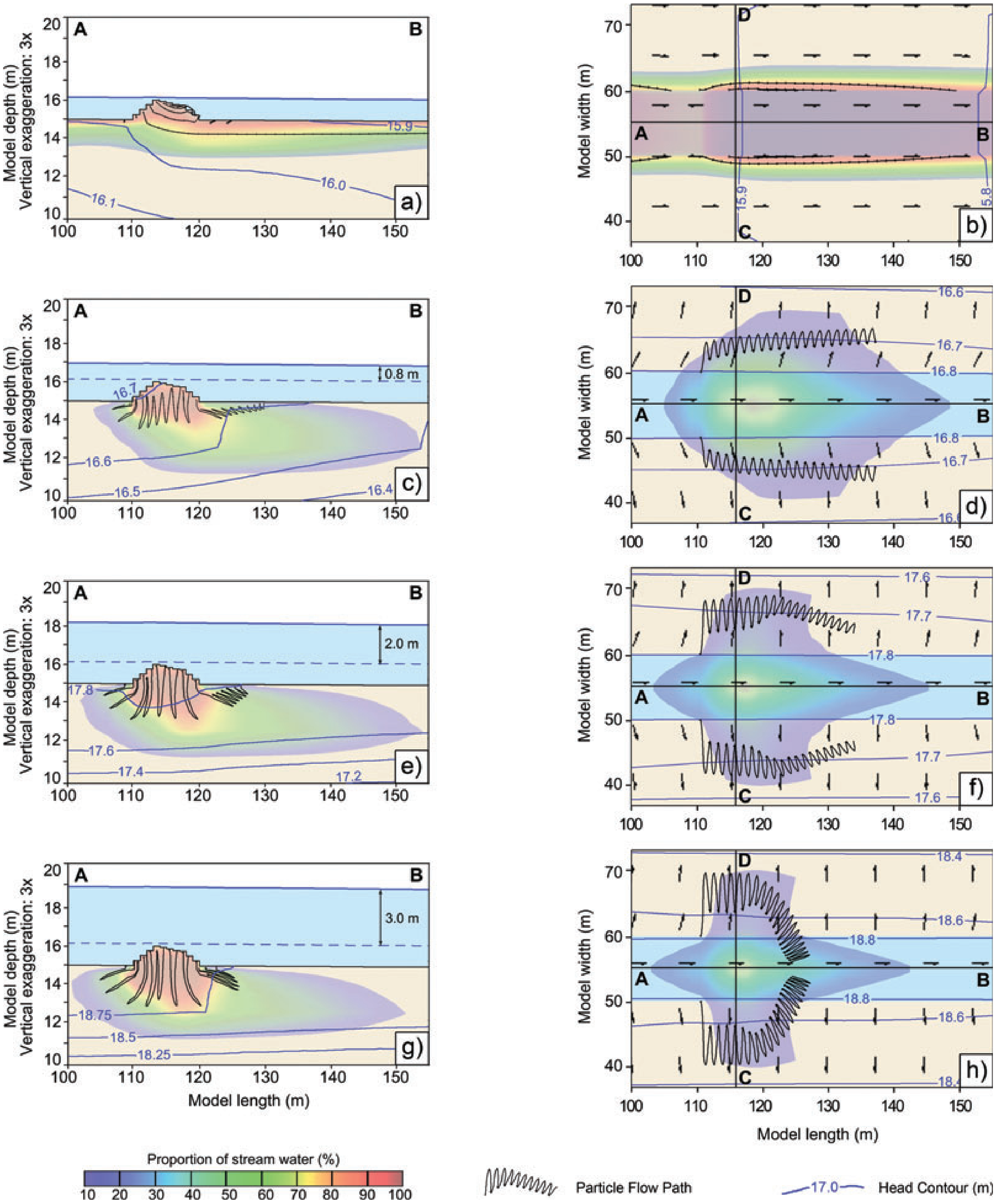

Figure 8. In the first column (a, c, e, and g) longitudinal cross sections AB through the middle riffle illustrate the effect on particle flow paths and residence times within the streambed during steady-state conditions and daily stream-stage fluctuations of 0.8, 2, and 3 m, respectively. In the second column (b, d, f, and h) plan views of the stream channel illustrate the effect on the flow paths and residence times of particles that enter bank storage lateral to the stream channel during steady-state conditions and daily stream-stage fluctuations of 0.8, 2, and 3 m, respectively. The color-shaded proportion of stream water profiles shown as background represents the proportion of stream water within the streambed and banks when daily stream stage is at its peak and were determined through MT3D simulations. The arrows indicate flow directions and the locations of cross sections AB and CD are shown in Figure 2.

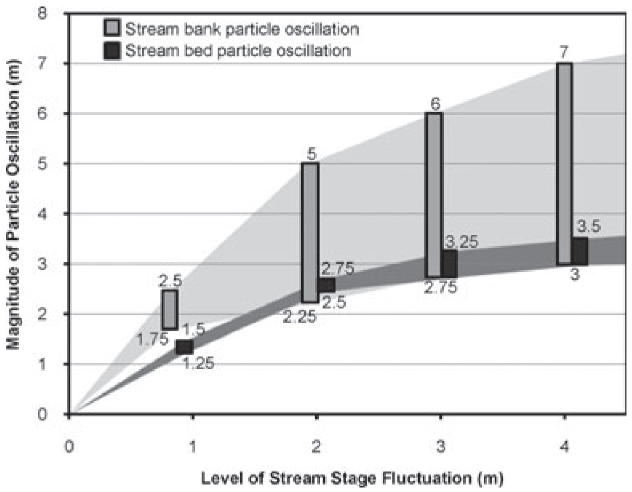

Figure 9. Amplitude of the particle oscillation within the stream bank and streambed as a function of stream-stage fluctuation.

Figure 11 provides a time series of results showing the degree of stream water/groundwater mixing for various depths beneath the upstream end of the riffle, in the middle portion of the riffle, and at the downstream end of the riffle when stream-stage data for the Magpie River (Figure 3b) are incorporated into the model. Assuming that the groundwater is solute-free and that the stream water can be considered as a source of solute of constant concentration, the figures effectively demonstrate how solute concentrations vary in the subsurface as a function of time.

All the plots exhibit the oscillatory behavior displayed by transported particles in the MODPATH simulations. As expected, the hyporheic zone close to the stream channel experiences a considerably higher proportion of stream water penetration as compared to deeper in the zone. More importantly, the upper part of the hyporheic zone experiences significantly larger oscillations in the relative proportions of stream water and groundwater, when compared to deeper hyporheic waters and this has important implications for the permanent and temporary hyporheos inhabiting the saturated pore space within the streambed, particularly in terms of nutrient supply, dissolved oxygen, and temperature. Similar observations in terms of oscillatory behavior and reduced amplitude with depth with respect to temperature and dissolved oxygen have been made by Hatch et al. (2006, 2010) and Nyberg et al. (2008).

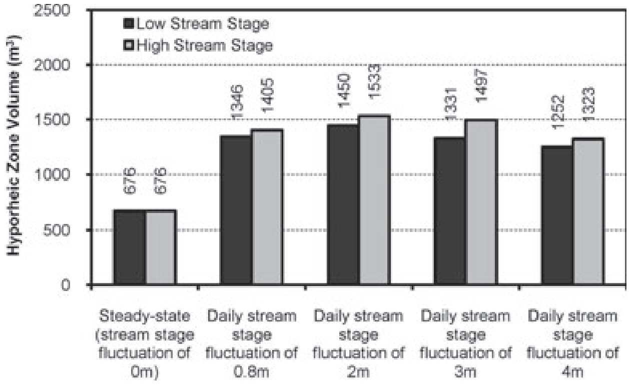

Figure 10. The influence of daily stream stage on the volume of the hyporheic zone, defined as the subsurface presence of at least 10% advected stream water.

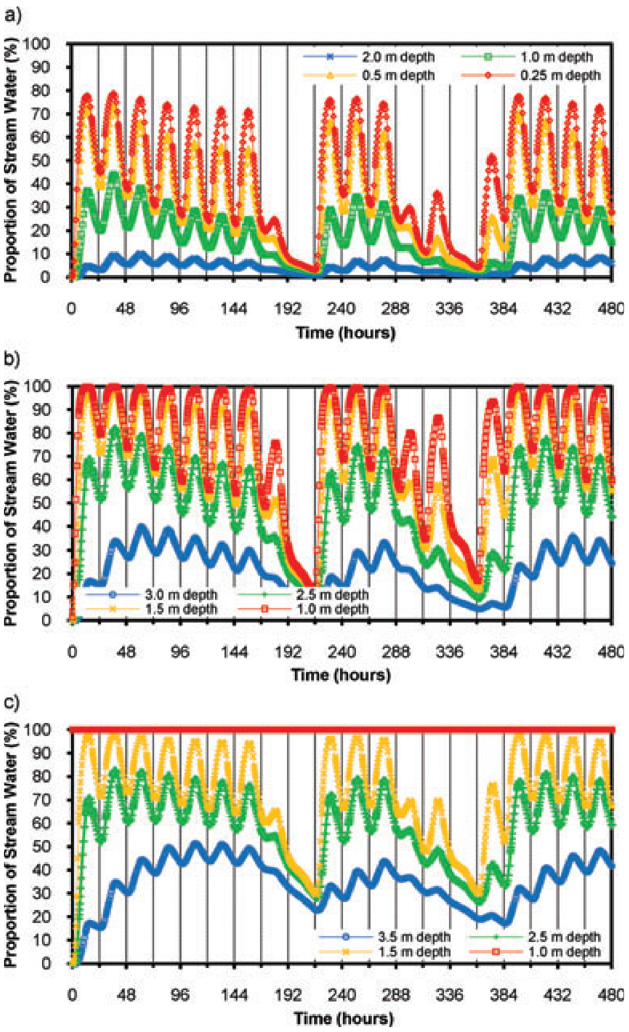

Figure 11. Simulated stream water/groundwater mixing at model observation wells located at the upstream (a), middle (b), and downstream (c) ends of the riffle as a function of depth for daily stream-stage fluctuations observed in the Magpie River shown in Figure 3b (well locations are shown in Figure 2).

Figure 12 summarizes the degree of stream water/groundwater mixing as a function of daily stream-stage fluctuation for the 0.8, 2, 3, and 4 m stream-stage fluctuation scenarios as daily frequency distributions (i.e., the daily variability in the proportion of stream water present at various depths within the streambed), for various depths in the model observation wells located at the upstream end of the riffle, in the middle portion of the riffle, and at the downstream end of the riffle, respectively. The locations of these wells are included in Figure 2.

The upstream end of the riffle (Figure 12a) is least affected by the stream-stage fluctuations but the changes

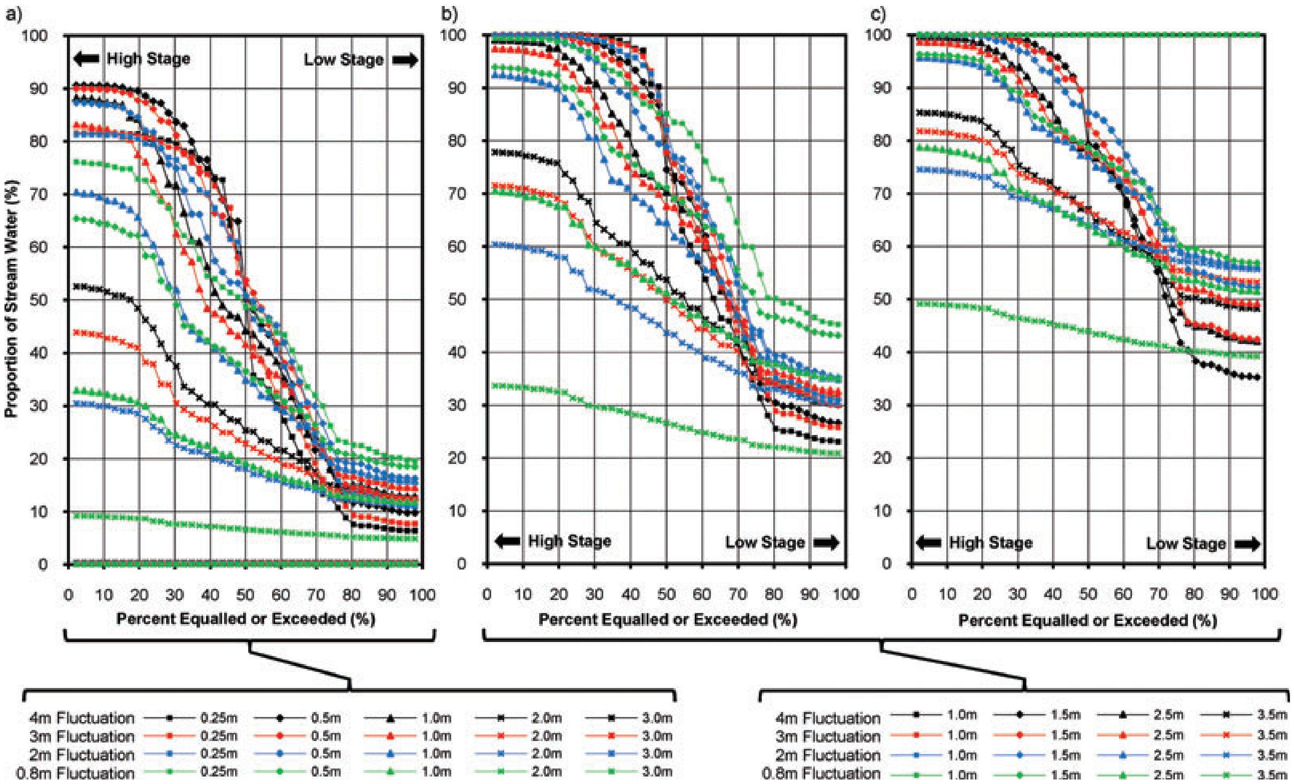

Figure 12. Frequency distribution plots showing the degree of stream water/groundwater mixing as a function of daily stream-stage fluctuation for various depths in the model observation wells located at (a) the upstream end of the riffle, (b) the crest of the riffle, and (c) the downstream end of the riffle (well locations are shown in Figure 2).

are still substantial. Significant daily variability in the proportion of stream water present (ranging from less than 20% to around 70% or more) occurs to a depth of 1 m for daily stream-stage fluctuations of 2 m or more. For daily stream-stage fluctuations of 0.8 m (Figure 12a) and 0.6 m (Figure 11a), similar effects are confined to a depth of only 0.5 m.

The most severe impacts occur beneath the middle and downstream ends of the riffle. Daily stream-stage fluctuations of 2 m or more may generate variations in the proportion of stream water present within the streambed that range from around 50% or less to almost 100% at depths of 2.5 m (Figure 12b and 12c). For daily stream-stage fluctuations of 0.8 m (Figure 12b and 12c) and 0.6 m (Figures 11b and 11c), the effects are slightly less severe but the proportion of stream water present still varies by 25 to 30 percentage points daily at a depth of 2.5 m.

The MODPATH and MT3D simulations provide complementary information. The MODPATH simulations indicate that solute residence times in the streambed are significantly reduced as the magnitude of daily stream-stage fluctuations increases. However, as shown by the MT3D simulations, this should not be taken to imply that the degree to which stream water and groundwater mix is similarly reduced. On the contrary, the results of the MT3D simulations show that the extent of mixing increases as the magnitude of daily stream-stage fluctuations increases. Although solute residence times may reduce to 1 day or less for daily stream-stage fluctuations greater than 1 m, the depth to which stream water penetrates the subsurface is considerably enhanced even though the proportion of stream water penetrating the subsurface may fluctuate by 90 percentage points during one daily cycle. Moreover, a close examination of the data presented in Figures 11 and 12 shows that such changes can occur within a 6-h period. The results are especially important for hyporheic communities that may survive gradual changes to their living conditions (e.g., water temperature, water chemistry, and flow velocities) by migrating to more hospitable aquatic habitats, but may be unable to respond to rapid changes caused by more extreme hydrological events.

Discussion

Previous research has demonstrated the utility of numerical groundwater flow models for the study of surface water/groundwater interactions and the hyporheic zone (Wroblicky et al. 1998; Kasahara and Wondzell 2003; Storey et al. 2003; Howard et al. 2006; Lautz and Siegel 2006), but these studies and similar research on the physiochemical aspects of the hyporheic zone have failed to consider the influence that temporally variable stream-stage conditions may have on solute flow paths and residence times, the size and extent of the hyporheic zone, and the amounts, rates, and depth of surface water/groundwater mixing. The research described here was able to address these issues by taking full advantage of field data collected from a transient yet strictly-regulated streamflow regime to create a series of predictive flow and transport models involving MODFLOW, MODPATH, and MT3D. Transient simulation of the groundwater flow system was performed with MODFLOW, whereas the MODPATH particle tracking package was used to determine solute flow paths and predict residence times. The MT3D mass transport package enabled reliable delineation of the hyporheic zone and allowed the degrees and rates of surface water penetration to be estimated.

Overall, this research demonstrates the highly dynamic nature of the hyporheic zone with fluctuations in stream stage radically affecting all aspects of hyporheic zone behavior. In turn, this has important implications for passive and active solute processing, water temperature dynamics, and hyporheic communities that inhabit the region. Hyporheic exchange flows are ecologically significant because they increase solute residence times and, therefore, contact times with chemically active subsurface sediments and biota, thereby enhancing chemical transformations (Dahm et al. 1998). The interaction of flow between streams and pore waters create regions of intensified biogeochemical activity and greatly influence the transfer of important dissolved and suspended substances, such as oxygen, carbon, nutrients, and etc. between streams and streambeds, which are important for the maintenance of healthy stream ecosystems (Williams 1993; Findlay 1995; Brunke and Gonser 1997; Sophocleous 2002). The hyporheic zone also moderates stream temperatures by receiving and storing heat from the stream, which is eventually advected back to the stream. Daily and annual temperature cycles in hyporheic discharge water are normally buffered and lagged relative to the daily and annual temperature cycles in streams, which has the effect of moderating both daily and annual stream temperature cycles (Arrigoni et al. 2008). In a sense, the hyporheic zone can generally be regarded as a relatively stable ecotone providing its inhabitants with a rich supply of nutrients and refuge from floods, droughts, extreme temperatures, and predators (Brunke and Gonser 1997). The timing and magnitude of hyporheic exchange flows are dependent on factors such as hydraulic gradients between the stream and groundwater and streambed topography and morphology as shown in this research, but can also be affected by other hydrological parameters such as hydraulic conductivity and porosity of the streambed (Woessner 2000; Storey et al. 2003; Lautz and Siegel 2006).

Although the MT3D simulations suggest extensive mixing of stream water with underlying groundwater, the MODPATH simulations show that residence times of solutes within the subsurface can be significantly reduced for higher magnitudes of daily stream-stage fluctuations. As a result, the chemical transformations that occur within the hyporheic zone that are important for the maintenance of healthy stream ecosystems and hyporheic communities may be significantly reduced. In addition, the moderating buffered and lagged effect of the temperature of hyporheic discharge water described by Arrigoni et al. (2008) could also be affected as a result of shorter residence times and could be an interesting topic for future research. Although hyporheic invertebrate communities may be able to respond relatively quickly to small flooding events with average return intervals of 1 year, they may not be able to respond quickly enough to daily flooding events, such as those that occur in regulated watersheds. In studies by Boulton and Stanley (1995), Olsen and Townsend (2005), and Hancock (2006) hyporheic invertebrate communities were found to recover to predisturbance levels within 7 days to a month from floods with annual return periods and were found to take as long as 140 days to recover from one-in-six year floods. These studies demonstrate the sensitivity of hyporheic communities to extreme hydrological events and suggest that hyporheic communities may not be able to fully recover to predisturbance levels from daily flooding events, such as daily flow and stream-stage fluctuations in regulated watersheds. How hyporheic communities react and evolve under these types of circumstances could be a topic of future research.

This research also indirectly emphasizes the usefulness of the collection of high-resolution temporal hydrologic data for the study of surface water and groundwater interactions. In this study, the field data reveal that head gradient reversals can occur over relatively short time periods, which may not otherwise be captured using longer measurement intervals. For example, the head gradient reversals for short duration streamflow surges, such as those observed between 288 and 384 h in Figure 3a and 3c, may not have been captured under daily or possibly not even under 6-h stream stage and piezometric head measurement intervals. Malcolm et al. (2006) also address the implications of high-resolution temporal data in hydroecological studies. The importance of the size of measurement intervals for the investigation of surface water/groundwater interactions would, of course, be guided by the objectives of the study.

Summary and Conclusions

This research was carried out to investigate the effect of variable stream stage and resulting transient flow behavior on the temporal development of the hyporheic zone and on solute flow paths. The results of this research demonstrate that variable stream stage is a critically important factor in hyporheic zone development. Specifically, this work has revealed that compared to steady-state conditions:

1. Stream-stage fluctuations produce sharply oscillating flow paths that can lead to premature ejection of hyporheic water. Under steady-state flow conditions (i.e., no fluctuations in stream stage), flow paths are generally smooth and residence times of surface water in the hyporheic zone are relatively long. Stream-stage fluctuations create fluctuating head gradients and flow reversals between the stream channel and streambed

and as the magnitude of stream-stage fluctuations increases so does the magnitude of the fluctuating head gradients between the stream channel and streambed. As a consequence, particle residence times beneath the stream riffle tend to be significantly reduced as the magnitude of head gradients between the stream channel and streambed increases. For particles entering the riffle 2 m upstream of the riffle crest, particle residence times range from 5 days to 1 day for daily stream-stage fluctuations of between 0.8 and 4 m, respectively, compared to a steady-state residence time of 67 days. Laterally adjacent to the stream channel, the fate of surface water that enters bank storage is made more complex by the competing influences of the natural water table and the fluctuating heads in the stream channel. Particle residence times within the stream banks tend to increase as the magnitude of stream-stage fluctuations increases until the bank storage heads exceed stream-stage heads. When bank storage heads exceed stream-stage heads, particle residence time within the stream banks is significantly reduced. The model simulations reveal that daily stream-stage fluctuations of 0.8 m tend to increase residence times adjacent to the stream; however, these times reduce significantly as the magnitudes of the stream-stage fluctuations increase.

2. Stream-stage fluctuations increase the rate and amount of mixing between stream water and groundwater. Under natural, steady-state conditions the vertical and lateral extent of stream water and groundwater mixing is relatively small and limited to a maximum depth of approximately 2 m beneath the streambed and 4 m laterally adjacent to the stream channel. Stream-stage fluctuations enhance the rate of stream water and groundwater mixing and generate cyclical oscillations in the proportion of surface water present. The most severe impacts occur beneath the middle and downstream ends of the riffle where daily stream-stage fluctuations of 2 m or more may generate variations in the proportion of stream water present that range from less than 50% to almost 100% at depths of 2.5 m.
3. Stream-stage fluctuations increase particle penetration depth. Under the steady-state conditions studied, particles penetrate the sediments beneath and adjacent to the stream channel by approximately 1 m. As discussed previously, daily fluctuations in stream stage generate head gradients and flow reversals between the stream channel and streambed and the magnitude of the fluctuating head gradients between the stream channel and streambed increases as the magnitude of stream-stage fluctuations increases. The increase in the magnitude of head gradients between the stream channel and streambed/banks significantly increases the depth to which particles penetrate the subsurface. For daily stream-stage fluctuations of 0.8, 2, and 3 m particles achieved depths of approximately 1.5, 1.75, and 2 m, respectively, beneath the stream channel and penetrated the stream banks by up to 10 m.
4. Stream-stage fluctuations increase the volume of the hyporheic zone, defined as the subsurface presence of at least 10% advected stream water. The modeling shows that the volume of the hyporheic zone approximately doubled when fluctuations in stream stage were introduced. The volume fluctuated by between 5% and 10% during the daily stream-stage cycle. The results also reveal that for daily stream-stage fluctuations of 2 m or greater, the volume of the hyporheic zone tends to decrease slightly. Again, this slight reduction in volume is attributed to the effect of bank storage, which tends to suppress the volume of the hyporheic zone once bank storage heads begin to exceed stream-stage heads.

This research and its implications for passive and active solute processing, water temperature dynamics, and hyporheic communities highlight the need to develop management tools that can minimize impacts. For example, this research demonstrates the utility of groundwater flow and transport models to investigate how various streamflow regimes may affect the degree of mixing between surface water and groundwater and ultimately, the physiochemical conditions within the hyporheic zone. Coupled with the knowledge of the hyporheos' tolerance to changes in physiochemical conditions, groundwater flow and transport modeling can then be used as a tool to test whether proposed water management actions such as dam operation would cause hyporheic residence time to be less than that required by hyporheic biota and to determine how to operate an upstream dam to achieve an optimal streamflow regime for hyporheic organisms living downstream of the dam. As indicated by the field data and simulated by the models, the raising and lowering of stream stage create strong reversals of hydraulic gradient in the subsurface which generate complex oscillating flow trajectories and rapidly changing advective velocities. The overall effect, as shown by the MT3D simulations, is to cause rapid changes in the relative proportions of groundwater and surface water present at any one point and a strong likelihood that the indigenous hyporheos will be exposed to rapidly changing temperature and chemical conditions. The degree to which the hyporheos will be affected will depend on their tolerance to rapid changes in water temperature and various chemical constituents and their ability to find a more suitable habitat should conditions prove inhospitable.

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