ground water

An Analysis of River Bank Slope and Unsaturated Flow Effects on Bank Storage

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Abstract

Recognizing the underlying mechanisms of bank storage and return flow is important for understanding streamflow hydrographs. Analytical models have been widely used to estimate the impacts of bank storage, but are often based on assumptions of conditions that are rarely found in the field, such as vertical river banks and saturated flow. Numerical simulations of bank storage and return flow in river-aquifer cross sections with vertical and sloping banks were undertaken using a fully-coupled, surface-subsurface flow model. Sloping river banks were found to increase the bank infiltration rates by 98% and storage volume by 40% for a bank slope of 3.4° from horizontal, and for a slope of 8.5°, delay bank return flow by more than four times compared with vertical river banks and saturated flow. The results suggested that conventional analytical approximations cannot adequately be used to quantify bank storage when bank slope is less than 60° from horizontal. Additionally, in the unconfined aquifers modeled, the analytical solutions did not accurately model bank storage and return flow even in rivers with vertical banks due to a violation of the dupuit assumption. Bank storage and return flow were also modeled for more realistic cross sections and river hydrograph from the Fitzroy River, Western Australia, to indicate the importance of accurately modeling sloping river banks at a field scale. Following a single wet season flood event of 12 m, results showed that it may take over 3.5 years for 50% of the bank storage volume to return to the river.

Introduction

Bank storage is an important hydrological process. It can reduce flood intensity at downstream sites as the flood hydrograph peak is reduced and delayed because event water is stored within the saturated and unsaturated zones of the alluvial aquifer. Bank storage then sustains flow in streams for some time after flood events as the stream stage recedes. Where regional groundwater is saline, bank storage can provide a fresh source of groundwater to streams for sustained periods of time following flow events.

Analytical models are widely used for estimating the dynamics of bank storage. Cooper and Rorabaugh (1963) provided analytical solutions for changes in watertable, flow, and bank storage occurring from a single flood wave oscillation in both finite and semi-infinite aquifers with a vertical river bank. They showed that in infinite aquifers, the return flow from bank storage after the flood wave has passed is very slow, with 50% of the bank storage volume returned to the river after 1.3 flood wave periods ($t = \tau$) and 90% returned after 18 flood wave periods. Rorabaugh (1964) then used these models to estimate changes in bank storage and groundwater contribution to streamflow for the Bitterroot River basin in Montana, USA. This included groundwater recharge from irrigation and precipitation.

Hall and Moench (1972) applied the convolution equation to solve for groundwater flow and head variations due to stream perturbations for four idealized cases

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of finite and semi-infinite aquifers with and without semipervious stream banks. This allowed input flood pulses of an arbitrary shape to be used. Moench et al. (1974) then used the convolution equation to model channel loss and base flow resulting from a reservoir release in central Oklahoma. On the basis of this method, Hunt (1990) used a perturbation approach to calculate an approximate flood-routing solution for the coupled groundwater and open channel flow equations in order to apply the bank storage effects discussed in the study by Moench et al. (1974) longitudinally down a river.

Limitations to the above-mentioned bank storage models include assumptions of homogeneity, valid Dupuit-Forchheimer conditions, fully penetrating streams, vertical river banks, and bank storage return under saturated conditions. These conditions are rarely found in the field, as highlighted by Sharp (1977). From our best knowledge, all of the analytical solutions are based on these assumptions. A quantitative assessment of most of these assumptions, however, has so far not been carried out.

Whiting and Pomeranets (1997) modeled return flow after an instantaneous river stage reduction from alluvial aquifers using a two-dimensional (2-D) numerical model with a free surface watertable and partially penetrating river. For the widest floodplain scenario presented, results were similar to those of Cooper and Rorabaugh (1963) and Rorabaugh (1964), with depletion of bank storage taking over 7 months for 50% of the water to drain from the bank for a sand aquifer. Recently, Chen and Chen (2003) and Chen et al. (2006) modeled streamflow infiltration and bank storage changes in a partially penetrating stream due to stage fluctuations using the numerical groundwater model, MODFLOW. They noted changes in the rate of infiltration and baseflow as a response to a series of parameters, including river hydrographs, hydraulic conductivity of the streambed and the underlying aquifer, and regional groundwater gradients. Both of these studies assumed vertical river banks, and did not explicitly model unsaturated zone processes using the full Richards Equation.

The first study to look at the impacts of sloping river banks was done by Li et al. (2008a). Dimensionless numerical simulations were undertaken to quantify bank storage in variably saturated, homogeneous, anisotropic aquifers with fully penetrating rivers with variable bank slopes, as a result of a simulated flood event using the model described by Boufadel et al. (1999). The study determined that bank storage was an increasing function of the rate of stream level rise, that smaller domain aspect ratios (or smaller bank slope) resulted in larger bank storage volumes due to a larger bank surface area for a given river stage. They also included an unsaturated zone, showing that materials with a low capillary suction resulted in higher volumes of bank storage. Also using dimensionless numerical relationships, Naba et al. (2002) and Li et al. (2008b) modeled similar problems associated with seepage flows and tidal seawater-groundwater interactions. The model used did not, however, consider the return flow of bank storage into the river, and therefore could not determine how these variables affected the rate of return flow.

McCallum et al. (2010) modeled solute dynamics during bank storage and return flow for confined and unconfined aquifers and rivers with vertical banks, including single wave and multiple streamflow wave events. They observed vertical head gradients present in the unsaturated models due to the pressure head moving more quickly in the deep part of the aquifer than at the water table. As a result, they suggested that it was important to model the unsaturated zone near the stream environment to accurately simulate the bank storage process. The study also showed that including the unsaturated zone reduced the magnitude of the return flow peak compared with models that assume saturated flow conditions.

For the conceptual approach of MODFLOW 2000 (Harbaugh et al., 2000), it is assumed that the stream is a rectangular shape with vertical banks and flux exchange through the stream bed. To model rivers with sloping banks, it would be necessary to create a stepped river profile with localized fine discretization, or use a depth dependent conductance term, which may be possible with the SFR2 package of MODFLOW (Niswonger and Prudic, 2005).

This paper explores the implications of assuming a vertical river bank and not allowing for variable saturation for calculations of bank storage fluxes and the return flow. Generic simulations use a regular cosine-wave variation in the river level and a triangular-shaped river to explore the role of bank slope on bank storage processes. Additional simulations using more realistic river hydrograph and floodplain geometries have been modeled on the Fitzroy River in Western Australia.

Conceptualization and Model Development

Generic Simulations

Generic simulations of a river-aquifer transect perpendicular to the river were developed, based on the semi-infinite aquifer example in the study by Cooper and Rorabaugh (1963), but additionally including unsaturated subsurface and surface flow domains. Rather than a vertical bank for the stream-aquifer interface, the model domain included a sloping section (Figure 1). Bank storage and return flow in a river with a straight, but sloping bank could then be simulated, allowing for direct comparison with the Cooper and Rorabaugh (1963) analytical solution. We initially model changes in head in the river following a cosine river stage input. Flow in the river is not simulated, but represented using a specified head boundary in the surface water domain.

The problem to be modeled involved both surface-water and porous media domains, therefore the fully-coupled, surface-subsurface flow model HydroGeoSphere (Therrien et al., 2006) was used. HydroGeoSphere simultaneously solves the diffusion-wave approximation of the Saint Venant equation for surface water flow, and the Richards' equation governing three-dimensional

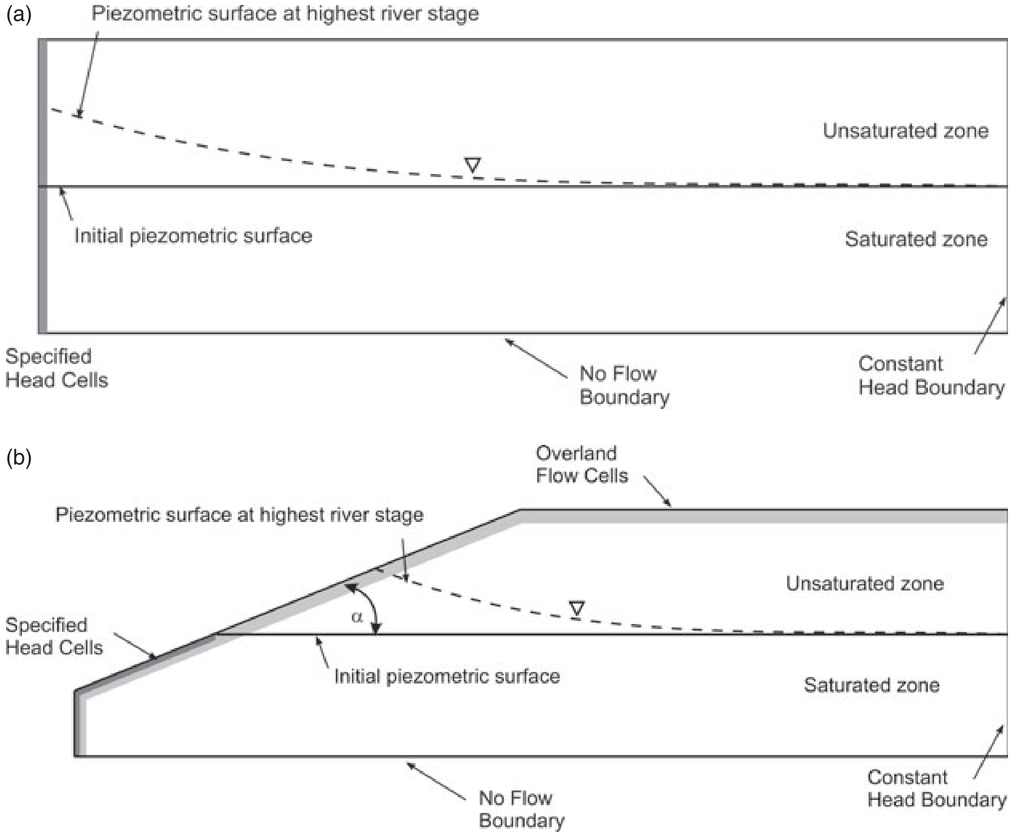

Figure 1. Bank cross sections used in the study with (a) vertical and (b) sloping river/aquifer interfaces (not to scale). Bank angle (α) is defined in degrees from a horizontal plane. Actual aquifer dimensions are 4 m thick and 250 m long.

(3-D) unsaturated/saturated subsurface flow with a physical coupling between the two domains. The ability of HydroGeoSphere to simulate bank storage and unsaturated zone processes in rivers with vertical banks has been verified by Brunner et al. (2009) and McCallum et al. (2010).

In this paper, the 250-m-wide, 4-m-thick aquifer was modeled as homogeneous and isotropic with an impermeable base and constant head on the right hand boundary. The stream was fully penetrating. Rainfall and evapotranspiration were not considered in this study. A series of river bank scenarios were modeled, based on bank slopes ranging from vertical (90° from horizontal) to an angle of 3.4° from horizontal, as shown in Table 1.

The model was run using the finite difference approach. To maintain a high level of accuracy when simulating coupled flows across the surface and variably saturated subsurface, the model required localized discretization near the river to 5 mm horizontally, and 20 mm vertically, particularly for the less steeply sloping examples. Further from the river, a coarser discretization of 10 m was applied. Adaptive time-stepping was used, with a maximum time-step of 0.1 d, and it was necessary to model the problem in steady state first in order to import initial saturation conditions. The initial river height and aquifer saturated thickness was 2.0 m.

The river flood pulse (Ψ) was defined using a specified head boundary applied to model cells within the permanently saturated part of the river, given by the equation:

$$\psi(t) = \begin{cases} (h_0/2)(1 - \cos \omega t), & \text{when } 0 \leq t \leq \tau \\ 0, & \text{when } t > \tau \end{cases} \tag{1}$$

where h_0 is the maximum rise in stage, t is the time since the beginning of the flood wave, τ is the duration of the wave and (Cooper and Rorabaugh 1963). The wave height h_0 was 1 m and the wave length was 5 d.

Table 1
Bank Slope Dimensions and Associated Angles Used in This Study

Angle (Degrees from a Horizontal Plane)	Slope 1:x
90	0
88.1	0.033
71.6	0.33
56.3	0.67
31	1.67
16.7	3.33
8.5	6.67
5.7	10.0
4.3	13.3
3.4	16.7

The aquifer is conceptualized as a zone of porous media, overlain by overland flow cells (Figure 1). The overland flow cells allow the river to flow up its banks, so that the river width increases during high flows. The domains were linked with a dual node arrangement, with a coupling length of 0.01 m.

Specified head cells were assigned to the overland flow cells beneath the initial water table position (Figure 1). Initial conditions included a constant pressure head within the aquifer and river, which were in equilibrium. The flood wave was applied to these cells. The overland flow parameters were chosen in a way so that there was no resistance and therefore no delay in the propagation of the wave in the surface domain. These consisted of a friction factor (Manning's n) of 10^{-5} s $\mathrm{m}^{-1/3}$ in both x and y directions, rill storage height of 0.00001 m and an obstruction storage height of 0 m.

Soil parameters for the porous media domain were based on a sandy loam from the soil types described by Carsel and Parrish (1988), shown in Table 2. The scenarios were also modeled using pseudo-soil parameters to remove the effect of the unsaturated zone. In HydroGeoSphere, it is not possible to switch off the unsaturated zone, but it is possible to get very close to this approximation by using pseudo-soil parameters, where the vertical hydraulic conductivity (K_v) is independent of the degree of saturation. This represented the system without an unsaturated zone, necessary to both validate the model against the analytical solution and separate the individual effects of river bank slope and unsaturated zone.

This model was initially used for a comparison with the analytical solution, and then to test the scenarios described above. Results were presented as the flux into the river bank varying with time and the proportion of water volume that had infiltrated the river bank that was still held in storage ("bank storage remaining") varying with dimensionless time. The results for a vertical bank matched the analytical solution for the proportion of bank storage remaining well. Results did not change with alterations of the right boundary condition between no-flow and constant head, and as the right boundary was located sufficiently far away that the results were not affected by the boundary condition, the aquifer approximated the semi-infinite system represented by the Cooper and Rorabaugh (1963) problem.

Table 2
Soil and Aquifer Parameters Used in the Scenarios Modeled

Parameter	Units	Scenario Values
Saturated water content (θ_s)	—	0.41
Residual water content (θ_r)	—	0.158
Saturated hydraulic conductivity (K_s)	m/d	1.06
Isotropic ratio (K_V:K_H)	—	1.0
van Genuchten α	m^{-1}	7.5
N (or β)	—	1.89
Specific storage (S_s)	—	10^{-4}

Realistic River Geometry and Hydrograph

A series of simulations were also performed using realistic river cross sections and flood hydrographs. For these simulations cross sections and hydrographs from the Fitzroy River in Western Australia were used. However, the modeling is intentionally not fully representative of the field situation, as the effects of riparian evapotranspiration and regional groundwater gradients, for example, would obscure the impacts of the sloping bank. The intent of the following section is to observe the isolated effects of river bank slope in a field-scale example.

The Fitzroy River is located in the Kimberley region of north Western Australia. It is one of Australia's largest unregulated rivers, characterized by braiding channels within a wide floodplain (Lindsay and Commander 2005). Annual rainfall is highly variable, ranging between 200 and 1000 mm at Fitzroy Crossing, and highly seasonal, with 90% of the rainfall occurring between November and March. Annual river discharge at Fitzroy Crossing varies between 300×10^3 m^3 and 25×10^6 m^3, with most of the flow occurring between December and March. When the river breaks its banks during high flows, floods will often extend several kilometers onto the floodplain.

The three different cross sections modeled were based on measured cross sections at different points along the river (Figure 2). These cross sections represented a cross section on a straight section of river (section 1), a steep cross section on the outside of a bend (section 2), and a stepped profile found on the inside of a river bend (section 3). The aquifer was 23 m thick at the thickest point, 9.7 m thick at the base of the river at low flow, and extended 2000 m from the river. The initial piezometric surface was at equilibrium with the river, at 70 m elevation. Soil and aquifer properties were for a sandy loam, using the parameters described for the generic modeling. The unsaturated zone was included in the simulations. For these models the river stage input, generated from hydrological data, varied by 12 m (from 70 to 82 m) over a period of 90 d, and represented a typical monsoonal flood event. The input river stage, derived from river hydrograph data, corresponds with an initial river depth of 0.32 m, and a maximum depth which overtops the river bank by

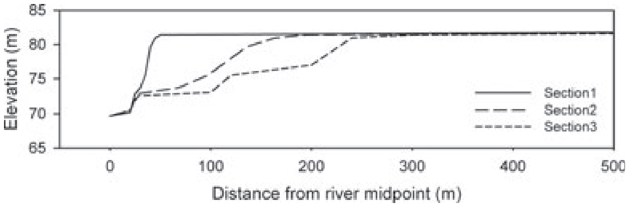

Figure 2. Cross sections from the Fitzroy River.

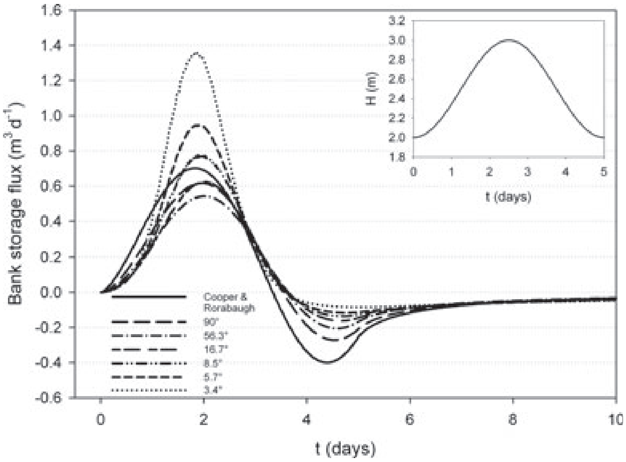

Figure 3. Flux into river bank for various river bank slope scenarios and the associated analytical solution. Inset shows the input wave pulse in stream stage.

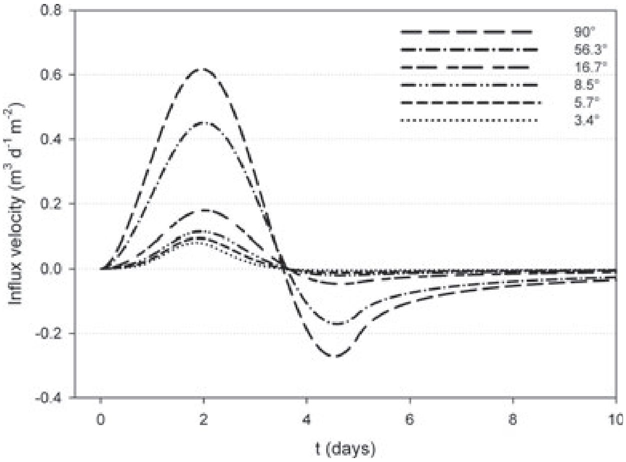

Figure 4. Influx velocity (volumetric exchange flux divided by the maximum saturated river bank surface area) for the river bank slope scenarios shown in Figure 3.

2.3 m and extends horizontally onto the floodplains by 15 m.

The Fitzroy River cross sections used a horizontal discretization of 0.2 m and a vertical discretization of 0.23 m.

Results

The flux into the river bank with time, and percent bank storage remaining within the aquifer are presented in the following sections for the modeled scenarios. The results are presented in three sections, covering the impacts of sloping banks, the inclusion of an unsaturated zone and realistic river geometry.

Quantifying the Effect of Sloping Banks

Figure 3 shows the groundwater flux from a river into an adjacent aquifer after a wave pulse (inset) in the stream stage. Initially, surface water flows into the alluvial aquifer, is stored within the groundwater, then the bank storage volume returns to the stream, indicated by a negative flux.

The flux peak from surface water to the groundwater domain through the river bank was found to be less than the analytical solution and delayed by 0.15 d for vertical and near vertical slopes, due to the effects of the unsaturated zone (discussed in detail in the following section). As the bank slope becomes more horizontal the flux peak initially decreases, from vertical to an angle of 56° then increases significantly for simulations with river banks that approached horizontal. Simulations for each of the bank angles described in Table 1 showed bank storage flux results that aligned with this trend. The peak flux reversal was found to be common to simulations with various saturated and unsaturated soil parameters, boundary conditions, and model discretization, which were undertaken but not presented in this paper.

Intuitively, as the bank slope becomes flatter, the maximum rate of flux, and also total bank storage volume, will increase due to the increasing cross-sectional area over which fluid exchange can occur. Figure 4 shows the change in inflow velocity (volumetric exchange flux divided by the maximum saturated river bank surface area) with time. Removing the effect of the cross-sectional area shows that the actual rate of flux per square metre of bank surface area decreases as the river bank becomes more horizontal. The increasing cross-sectional area and opposing decreasing influx velocity as the river bank approaches horizontal explains the peak reversal.

The peak rate of return flow decreases with more horizontal slopes as the water has further to travel back to the river. For the flattest river bank at the highest hydrograph stage, the width of the river increases by 16.7 m. This means that water infiltrating the bank must travel up to 16.7 m before returning to the river as baseflow. There is also a much larger area of unsaturated zone in which bank storage water is held, thereby damping and delaying the return flow (Figure 5).

Cooper and Rorabaugh (1963) found for their vertical bank analytical model, that bank storage declined more slowly than for finite aquifers and at a rate shown in Figure 6. Approximately 50% of the bank storage had returned to the river after 0.6 wave periods (t/τ^*), while for rivers with sloping banks, the numerical modeling indicated much slower rates of return (Figure 6). The variable "τ" represents the flood wave period and the * denotes that measurement begins after the maximum bank storage volume, that is at the commencement of net flow out of the aquifer. For the 8.5° slope scenario, 50% of the bank storage had returned after 2.67 wave periods; 2.6 times longer than the vertical case, and more than four times longer than the confined analytical solution.

The bank storage return curve for the vertical scenario plotted higher than the analytical solution due to the inclusion of an unsaturated zone which delayed the return of groundwater to the river. The storage volume in the

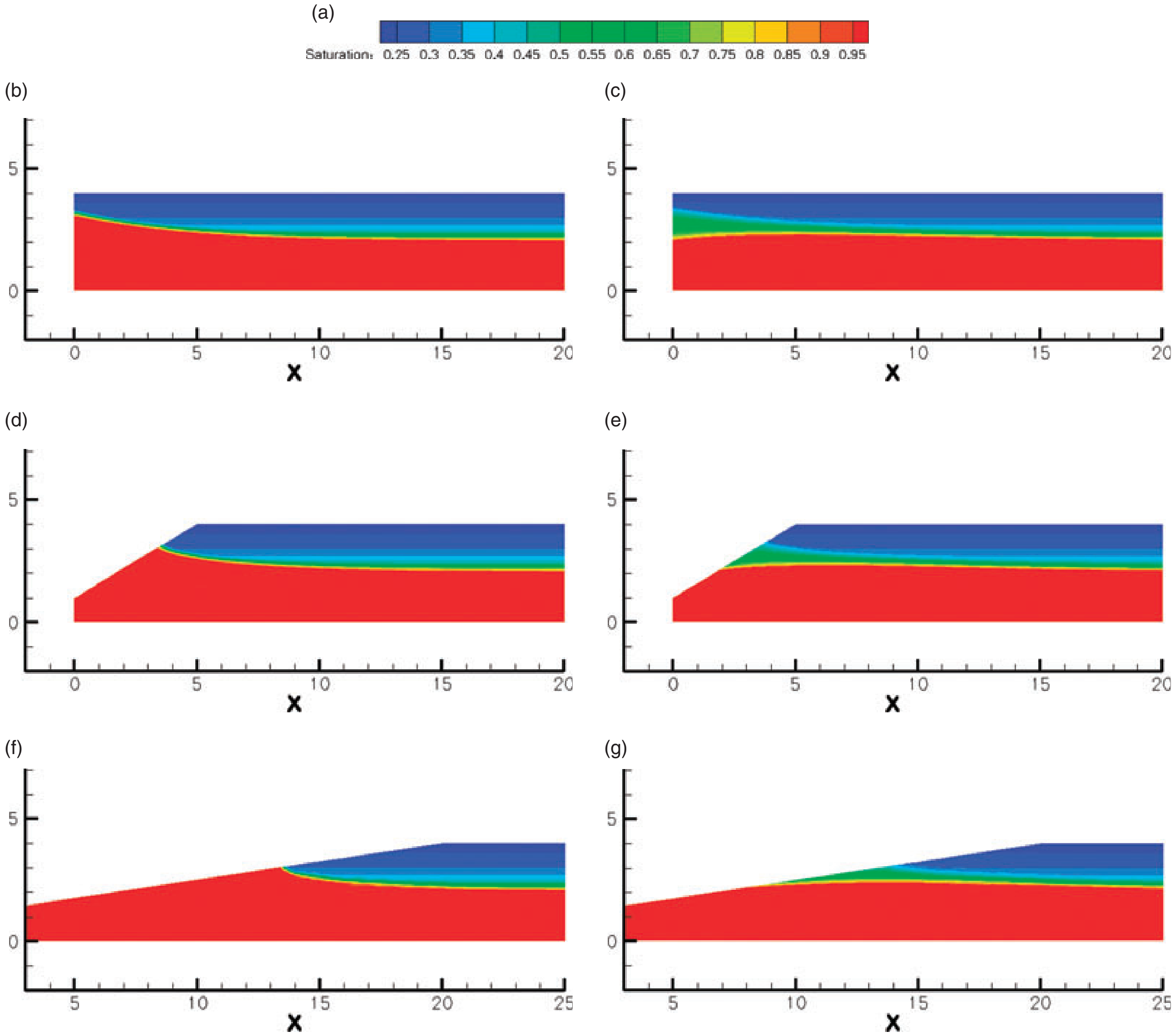

Figure 5. Saturation profiles for the vertical river bank for the vertical, 31° and 8.5° scenarios, at $t = 2.5$ d (left) and $t = 5.0$ d (right).

capillary fringe took longer to drain on the decline of the flood impulse than it would have if modeled without an unsaturated zone.

Quantifying the Effect of the Unsaturated Zone

Investigation of the effects of a sloping bank on bank storage and return flow required both a surface water domain and unsaturated zone to model water movement from the river, up the bank slope and infiltration into the aquifer. It was therefore necessary to isolate the differences from the analytical solution due to the sloping bank from those due to the surface water domain and unsaturated zone. The model setup was the same as for the previous section, except for the parameterization of the unsaturated zone. However, in order to quantify the effect of including the unsaturated zone, the model runs were repeated with pseudo-soil parameters. In the pseudo-soil relationship, the porous media is assigned a saturation of zero above the water table and one below it. Relative permeability is applied to horizontal flow only and water travels vertically under saturated hydraulic conductivity conditions, bringing the model closer to the analytical solution. Flux into the river bank with time using the saturated-unsaturated and saturated modeling conditions for the vertical bank case are shown in Figure 7.

The explicit inclusion of an unsaturated zone was found to reduce the peak of the infiltration flux and bank storage volume by around 23%. This suggests that the unsaturated zone has a damping effect on the rate of flux into the bank as the soil must become saturated before it can convey substantial volumes of water. Note that the flux curves did not match the Cooper and Rorabaugh (1963) confined aquifer solution exactly due to the variable aquifer transmissivity in the numerical models, which therefore violated the dupuit assumption of the analytical solution.

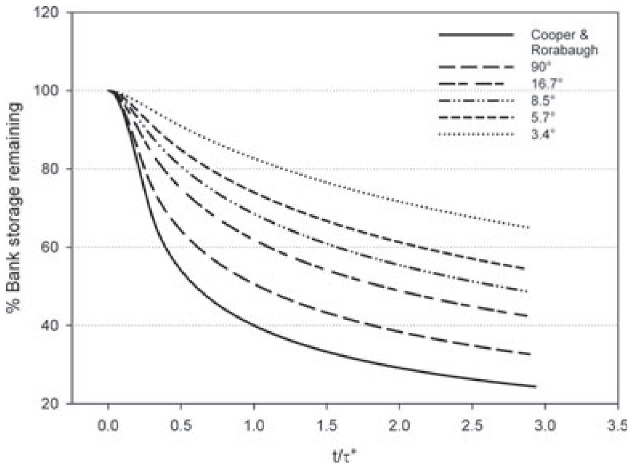

Figure 6. Percent bank storage volume remaining in the aquifer for various river bank slope scenarios and the analytical solution based on Cooper and Rorabaugh (1963). The variable "τ" represents the flood wave period and the * denotes that measurement begins after the maximum bank storage volume, that is at the commencement of net flow out of the aquifer.

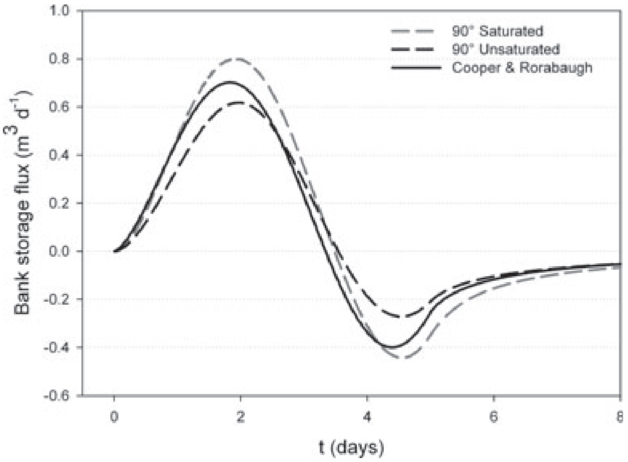

Figure 7. Flux into river bank for the Cooper and Rorabaugh (1963) solution, unsaturated, pseudo-soil (saturated), and vertical sloped bank scenarios.

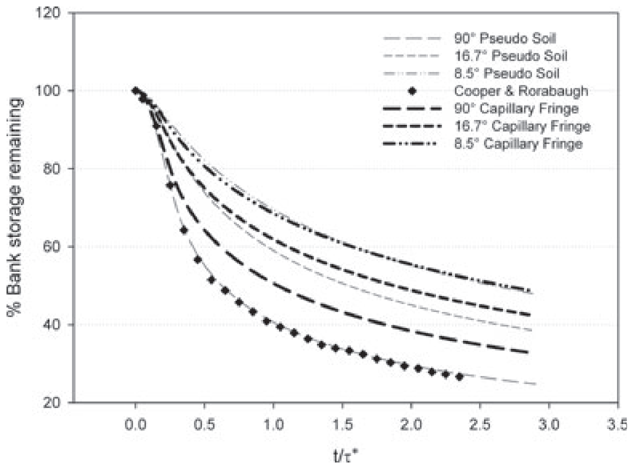

Figure 8. Percent bank storage volume remaining for analytical, unsaturated, and pseudo-soil sloped bank scenarios; t/τ^* measurement after the maximum bank storage volume or at commencement of net flow out of the aquifer.

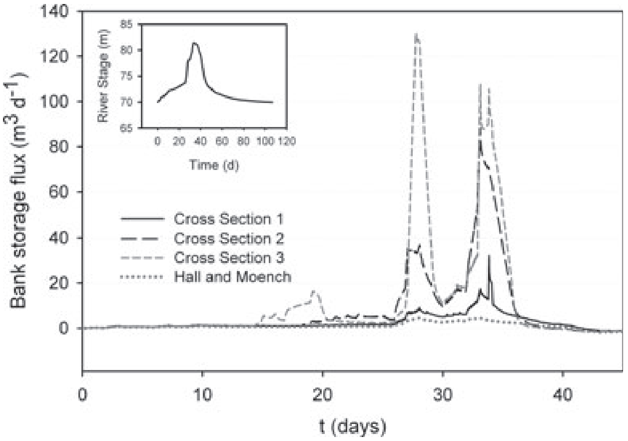

Figure 9. Flux into river bank for example cross sections from the Fitzroy River, Western Australia, compared with the Hall and Moench (1972) solution. Inset shows the river hydrograph applied as a specified head.

The return flow rate was also lower when an unsaturated zone was modeled explicitly (Figure 8). Using pseudo-soil parameters, the curve of bank storage volume remaining for dimensionless time (number of wave periods after the maximum bank storage volume) for the vertical bank followed the Cooper and Rorabaugh (1963) analytical solution. With the unsaturated zone included, the time taken for 50% of the bank storage to return to the river increased by 64%.

For the sloping bank scenarios, return flow was found to be less sensitive to the explicit modeling of an unsaturated zone, and the difference between the treatments decreased as the bank angle was reduced. For the 8.5° bank slope scenario, the curves of bank storage remaining for saturated-unsaturated and saturated models were almost identical. Including the unsaturated zone increased the time taken for 50% of the bank storage to return to the river by only 6%. Other considerations regarding the influence of the unsaturated zone below a disconnected stream are found by Brunner et al. (2010).

Realistic River Geometry

For the Fitzroy River simulations, the bank storage flux and percent bank storage remaining with dimensionless time are shown in Figures 9 and 10 respectively.

Figure 9 shows very high rates of influx associated with flatter steps on the profile. These steps had a much smaller angle than the examples modeled in the previous sections, with angles of the order of 0.4° to 1.5°. It appears that bank storage starts at around 15 d, despite the hydrograph starting to increase immediately. However, bank storage flux is extremely low in the first 15 d as the river stage moves up the steeper sections of bank compared with the dramatic increase in infiltration as the

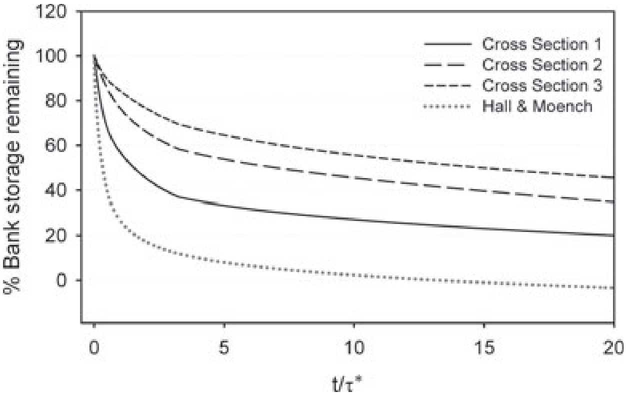

Figure 10. Percent bank storage volume remaining for example cross sections from the Fitzroy River, Western Australia, compared with the analytical solution for a vertical bank. The Hall and Moench (1972) solution was used to allow an irregular input wave. It produced the same results as the Cooper and Rorabaugh (1963) solution with a sinusoidal wave.

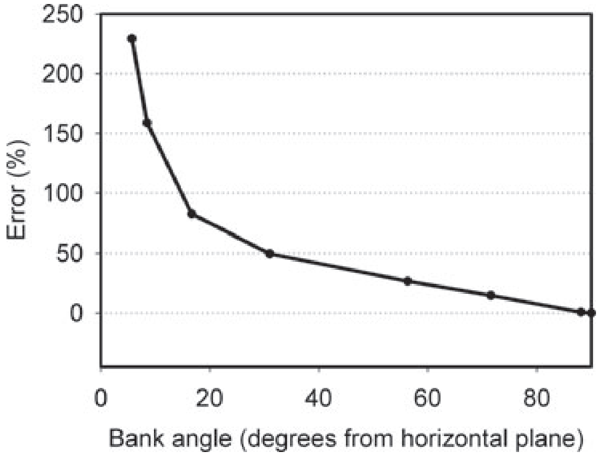

Figure 11. Relative error in the time taken for 50% of bank storage volume to return to the river due to the assumption of vertical banks. Actual bank angle is plotted against percentage variation from the 50% return time of a vertical bank.

wave reaches the flatter profiles higher up the bank. The bank storage flux curves for the numerical models also show two peaks, or three in the case of cross section 3. This is due to two effects: firstly the number of flatter segments in the cross-sectional profiles (two for section 2 and three for section 3) and secondly the shape of the input wave. There are two rapid rises in the river hydrograph, with a small plateau in between. As bank storage flux is related to the rate of change of river stage rather than the absolute stage, the results for cross section 1 and the Hall and Moench solution also reflect the two peaks, despite not having any flatter sections in their profiles. For very steep sections of bank (e.g., cross section 1) the bank storage flux rate followed the analytical solution (Figure 9). The presence of a resistive layer on the river bank, such as a deposited silt layer, would restrict the inflow of bank storage, particularly for flatter parts of the cross section and overbank flow recharge.

The return flow for all three cross sections was delayed compared with the Hall and Moench (1972) analytical solution (Figure 10). The Hall and Moench solution allowed the use of an irregular river hydrograph with a semi-infinite aquifer with a vertical river bank. It produced the same result as the Cooper and Rorabaugh (1963) solution with a sinusoidal wave input. Since the duration of the wave (τ) is around 90 d, this figure suggests that for the flatter cross sections it may take over three and a half years for 50% of the bank storage volume to return to the river. In reality, evapotranspiration from riparian vegetation is likely to use some of this water and return flow to the river would be less than shown here.

Discussion

Slope Angle

As a river bank slope angle decreases, the time taken for bank storage to return to the river increases. This is thought to be due to the longer distance to travel from where the greatest volume of water infiltrates into the bank back to the river after the wave has passed (Figure 5). Thus, numerical models that represent a river with vertical bank slope can significantly under-predict return times for rivers with sloping banks. Figure 11 shows the error, or percentage difference in the time taken for 50% of the bank storage volume to return to the river (t_{50}) for sloping banks compared with a vertical bank standard, plotted against the river bank angle. This gives an indication of the error associated with assuming a vertical bank in a numerical model of rivers with sloping banks. This suggests that in order to keep modeling errors to within a reasonable limit, rivers with bank slope angles of less than 60° should be modeled in a way that includes a sloping bank rather than using an analytical solution or numerical model that assumes vertical banks.

Unsaturated Zone

The explicit inclusion of an unsaturated zone in numerical modeling reduced the volume of bank storage in the vertical bank example by 23%. Birkhead and James (2002) also note that, generally, the Cooper and Rorabaugh (1963) analytical model has a tendency to underestimate the seepage into and out of the bank zone due to the assumption of the constant transmissivity and that modeled bank seepage rates reduce when flow in the unsaturated zone is accounted for. This finding is important as often bank storage is modeled with either analytical or numerical groundwater models that do not include an explicit unsaturated zone (Hunt 1990; Chen and Chen 2003; Chen et al. 2006).

The importance of including an unsaturated zone to model bank storage and return depends on the aquifer characteristics. The unsaturated zone is more critical for modeling aquifers with a lower transmissivity, such as silts or loams, or where aquifers are thin relative to the height of the flood pulse. The duration of the flood pulse relative to aquifer transmissivity is also likely to be important.

General

The modeling presented in this paper did not include other parameters that will affect bank storage and return flow, including:

- aquifer transmissivity, likely to result in higher bank storage with higher transmissivity;
- wave duration relative to transmissivity, with increasing wave duration likely to increase the bank storage volume and delay return flow;
- aquifer thickness to wave height ratio, with potentially less impact of slope and unsaturated zone as the aquifer thickness increases;
- the inclusion of a silt layer overlying the riverbank, reducing and damping infiltration and return flow;
- the state of connection between river and aquifer: gaining, losing, or losing disconnected, particularly impacting the proportion of bank storage returning to the river;
- regional groundwater gradients resulting from distant recharge, increasing the rate of return flow; and
- evapotranspiration from riparian vegetation, which is expected to significantly reduce return flow rates.

There is no provision for the last three points to be included in the analytical solutions for bank storage and return flow.

Although it was not modeled in the simulations described above, bank infiltration will be lower, and return flow faster than presented in this study if the regional water table was sloping toward the stream. This has been confirmed by Chen et al. (2006) and McCallum et al. (2010). Similarly, evapotranspiration in the riparian zone will locally draw down the water table in the vicinity of the river, increasing the rate of influx and reducing the rate of return flow (Chen et al., 2006). These effects are particularly pertinent for the field application results shown in Figure 10. A sloping regional watertable will decrease the peak bank storage fluxes and hasten the return flow, while evapotranspiration from riparian vegetation will act in an opposing way, increasing bank storage and reducing return flow. The overall impact on such a system will depend on local characteristics, and requires further modeling backed up by additional field monitoring to parameterise the model.

Conclusions

Numerical simulations of bank storage and return flow were undertaken for generic river—aquifer cross sections with straight but sloping river banks. Sloping river banks were found to increase the peak bank storage flux and volume, and delay the rate of flow returning to the river. Explicit modeling of an unsaturated zone decreased bank storage and the rate of influx, but delayed the rate of return flow, more significantly in rivers with vertical banks.

The analyses on a sandy loam aquifer presented in this paper suggest that further investigation of the application of analytical and numerical approximations that assume vertical river banks, such as Cooper and Rorabaugh (1963), to real scenarios should be undertaken. For the analyses undertaken in this paper, a bank slope angle of less than 60° from a horizontal plane was a trigger to consider more sophisticated methods of analysis. Similarly, the potential errors from applying these approximations to thin, silty, or loamy aquifers where an unsaturated zone is likely to have a significant effect should be considered.

Bank storage and return flow were also modeled in three representative cross sections of the Fitzroy River, Western Australia, using a single flood pulse derived from historical hydrograph information. Results suggested that for the flatter cross sections it may take over three and a half years for 50% of the bank storage volume to return to the river.

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