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Incorporating floodplain groundwater interactions in river modeling

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Abstract: Understanding surface-groundwater interactions should be an integral part of water resource management. Groundwater extraction, recharge, overbank flooding, bank storage, and evapotranspiration are key floodplain processes that impact the water balance and have implications for ecosystem health. Tools available for modeling these processes have high data requirements, which limit their usefulness. We propose an intermediate complexity model with minimal data requirements to model these processes.

The Floodplain Model simulates flow in an unconfined aquifer with direct hydraulic connection to a lowland river channel. The model is underpinned by explicit analytical solutions that estimate changes in aquifer pressure heads and exchange fluxes between the river and the aquifer due to random time-varying combinations of pumping, recharge, evapotranspiration, and river stage heights that include overbank flow. It assumes a linear system and uses superposition to aggregate the impacts of individual stresses.

The Floodplain Model will be operable in two forms: (1) as a stand-alone tool for explicit modeling of floodplain processes, and (2) as an optional module available in RiverManager for implementation in areas where groundwater data is available. RiverManager is a modeling tool under development, which is being designed to meet the needs of river planners and managers across Australia. In this paper, we describe the theory and software development of the stand-alone version of the Floodplain Model. The software shell for the model is written in C#. It combines elements of The Invisible Modeling Environment (TIME) and specifically written classes to form a robust framework for the model. We present preliminary results from the prototype model with validation against an existing industry standard numerical model.

Keywords: *Surface-ground water interaction, Floodplain, Bank storage, Pumping, Recharge, ET*

1. INTRODUCTION

The critical issues of water resource availability and ecological sustainability have highlighted the need to integrate surface-groundwater (SW-GW) interactions in both groundwater and surface water models. Recent initiatives by the Australian government such as the Murray-Darling Basin Sustainable Yields Project have emphasized this need and demonstrated the lack of tools that can model those interactions on a large scale (http://www.csiro.au/partnerships/MDBSY.html). The eWater Cooperative Research Centre (CRC) and the National Water Commission (NWC) have recognized the importance of this issue and thus established the the 'Groundwater Surface Water Interaction Tool (GSWIT)' project. There are two main aspects to GSWIT; firstly, to add SW-GW interaction functionality to catchment-scale water and solute generation models (e.g., WaterCAST, which is outside the scope of this paper; refer to Gilfedder *et. al* 2009 for details), and secondly, to add SW-GW interaction functionality to river management models (e.g., RiverManager, refer to http://www.ewatercrc.com.au). The model described in this paper relates to the latter task.

Rassam and Werner (2008) conducted a comprehensive literature review and highlighted the need to develop SW-GW interactions models with varying levels of complexity (low to intermediate) depending on data availability. Hence, the SW-GW interaction module for RiverManager will be implemented at two levels of complexity. In data poor areas, SW-GW interactions will be modeled assuming a static water table in time but variable in space (underpinned by SW-GW connectivity mapping). However, in areas where groundwater data is available, the groundwater table will be dynamically modeled and linked to spatial and temporal changes in river stage heights. This is achieved by linking RiverManager to the Floodplain Model described herein. It will explicitly account for surface-groundwater interactions, in addition to river and floodplain/wetland interactions. The scope of this paper is limited to describing the stand-alone version of the Floodplain Model, which will be integrated in the near future into RiverManager.

The conceptualization and stand-alone application of the Floodplain Model is presented in this paper. Firstly, we describe the conceptual model and underlying assumptions. Secondly, we discuss the processes and the analytical solutions that underpin their modelling. Thirdly, we discuss the software development, and we conclude by presenting preliminary results, which validate the model outputs against numerical simulations.

2. CONCEPTUAL MODEL AND UNDERLYING ASSUMPTIONS

The conceptualisation of the Floodplain Model is shown in Figure 1. We model flow in an unconfined semi-infinite aquifer, which is in full hydraulic connection to a nearby river.

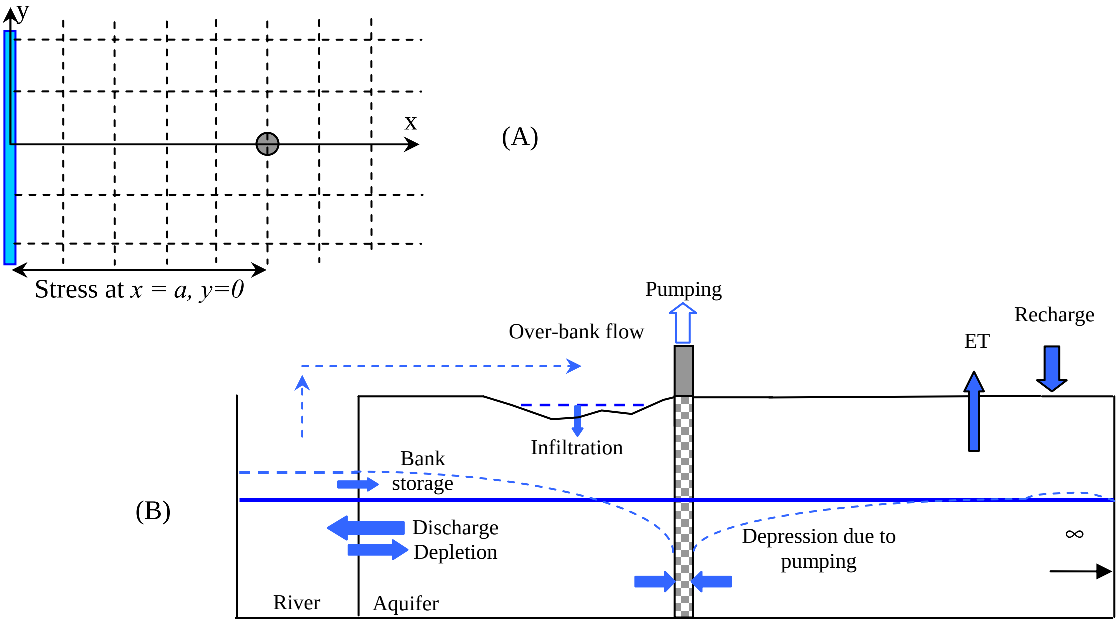


Figure 1. Conceptualisation of the Floodplain Model

We assume a single-layered homogenous aquifer that fully penetrates a straight river (which acts as a constant head boundary) with other aquifer boundaries extending to infinity (see Figure 1A, plan view). Linearity is assumed whereby aquifer parameters (transmissivity T) are constant in space and time. This means that transient changes in T (e.g., as a result of drawdown during pumping) are neglected; this assumption holds as long as the magnitude of the head change is small relative to the saturated aquifer thickness. The assumption of linearity allows superposition, whereby the impacts of individual stresses can be integrated to obtain an overall impact on the system. Rassam *et al.* (2004) provided a comprehensive study of the versatility of linearity and superposition. The initial water table is assumed to be in equilibrium with the nearby river.

The Floodplain Model operates on a river reach scale. It explicitly models recharge, bank storage, evapotranspiration (ET), and stream depletion due to groundwater pumping. The model is underpinned by explicit analytical solutions that can handle arbitrary inputs (in time). The modelled processes are schematically shown in Figure 1B (sectional view). The model estimates the exchange fluxes between the river and the aquifer as well estimating two-dimensional pressure heads in the aquifer as a result of any combination of processes.

3. ANALYTICAL SOLUTIONS AND MODELLED PROCESSES

Flow in an unconfined aquifer is modelled using the linearized Boussinesq equation, which is given by:

$$\frac{\partial h}{\partial t} = \frac{Kh^*}{S}\frac{\partial^2 h}{\partial x^2} \qquad (1)$$

where S is the specific yield, K is the saturated hydraulic conductivity, h is the height of the water table in the unconfined aquifer, h^* is an average height of water table, x is the distance from the stream in the horizontal plane, and t is time (Bear, 1972). Equation (1) is applicable when the fluctuations in the water table are small compared to the saturated thickness of the aquifer. Equation (1) has the form of a diffusion equation where T/S is the diffusivity (D) and transmissivity $T=Kh^*$. The boundary condition at x=0 is the Dirichlet condition $h(0,t)=h_o(t)$, where $h_o(t)$ is the river height.

We implement the splines method of Knight and Rassam (2007), which allows arbitrary stresses (of river stage height or recharge) to be used as input signals. The method provides an explicit analytical solution (for pressure head or flux) for a smooth pulse input of stream stage height or recharge/pumping. The methodology is summarized as follows: (1) we describe the random input pulse with a series of cubic basis splines; every stage height or recharge is described using three consecutive splines and some numerical coefficients, (2) the unit cubic basis spline is the unit building block, which can be described by a series of power functions, due to linearity, we can find the response for the cubic basis spline from the response of the component power functions, (3) having used a number of basis splines to describe the random input pulse, we can use the cubic spline response and the numerical coefficients (used to fit the stage height data) to formulate an explicit analytical solution for the groundwater head/flux response due to this random input pulse. The response due an arbitrary input signal (river stage height or recharge time series) is given by:

$$f(t) = \sum_{n=-1}^{N+1} a_n F_n^3(t) \; , \qquad (2)$$

$F_n^3(t)$ is the flux or head response corresponding to a unit cubic basis spline input (e.g., those given by Equations 3, 4, or 5), and a_n is a numeric coefficient. More details on the splines method are found in Knight (2006). In the following section, we briefly discuss the modelled processes and the underlying analytical solutions.

3.1. Bank Storage

During inter-storm periods there is a stream-ward hydraulic gradient in gaining streams that maintains groundwater discharge into them. Stream water levels rise in response to runoff and, in most cases, results in the reversing of the hydraulic gradient, which induces a net flux into the floodplain. This water is temporarily stored in the floodplain and is slowly released back to the stream when the stream water level drops and the gradient towards the stream is re-established. This phenomenon is referred to as bank storage.

The aquifer pressure heads during bank storage are calculated following the methodology presented by Knight and Rassam (2007). The flux rate density into the bank at x=0 due to unit cubic spline input (representing a unit flood wave in the river) is given by:

$$f_n^3(t)=\frac{8}{15}\sqrt{\frac{CS}{\pi}}\left\{(t-t_{n-2})_+^{5/2}-4(t-t_{n-1})_+^{5/2}+6(t-t_n)_+^{5/2}-4(t-t_{n+1})_+^{5/2}+(t-t_{n+2})_+^{5/2}\right\}/\Delta t^3 \tag{3}$$

The cumulative flux into the bank at $x=0$ is given by:

$$F_n^3(t)=\frac{16}{105}\sqrt{\frac{CS}{\pi}}\left\{(t-t_{n-2})_+^{7/2}-4(t-t_{n-1})_+^{7/2}+6(t-t_n)_+^{7/2}-4(t-t_{n+1})_+^{7/2}+(t-t_{n+2})_+^{7/2}\right\}/\Delta t^3 \tag{4}$$

Where $C=K/h^*$ represents aquifer conductance, the superscript (3) refers to the third degree (cubic) splines used here, n is the number of knots (corresponding to the number of data points in the input time series), and t is time.

3.2. Overbank Flow

Overland flow is described as the water that flows over the ground either as quasi-laminar sheet flow. Overland flow is influenced by spatial variation in topography, vegetation, soil characteristics and geology. Overbank flow becomes a significant and a longer term recharge mechanism when depression storages are filled. The Floodplain Model does not model overbank surface flow and the formation of floodplain wetlands. However, it does model infiltration from such wetlands and estimates the time delay for this component until it reaches the water table, which is then handled as a recharge source. The resulting changes in pressure heads and fluxes due to this recharge are discussed in the next section. A simple square wave approach is used to model the delay in the unsaturated zone. However, this delay is likely to be insignificant in areas with shallow groundwater tables (which is the most likely scenario in floodplains). The spatial distribution of the formed wetlands and the volume of water available after large flood events that cause overland flow are pre-required as input data.

3.3. Groundwater Pumping and Recharge

The impacts of groundwater pumping and recharge on aquifer pressure heads and SW-GW exchange fluxes are exactly opposite, i.e., pumping is a negative recharge. Consequently, the analytical solutions that underpin them are mathematically identical. Therefore, we shall refer to them here as ‘stresses’.

The analytical solution for estimating SW-GW exchange fluxes due to a change in aquifer stress (e.g., increase in discharge to the river as a result of increased recharge) is mathematically identical to solution for aquifer pressure heads as a result of a change in river stage heights. One only needs to replace the stage heights input signal by the recharge input signal as the response scales linearly with the input signal. Therefore, we use the same solutions presented by Knight and Rassam (2007) to estimate the exchange fluxes. The pressure head (h) at any grid point in the flow domain (x, y) at any time (t) is given by:

$$h(x,y,a,t)=\frac{t^k}{4k!\pi T}\left[V_k\left(\frac{r_1^2}{4Dt}\right)-V_k\left(\frac{r_2^2}{4Dt}\right)\right] \tag{5}$$

with the functions V_k (z) satisfying the same recurrence relation as the Laguerre polynomials L_k (-z) with negative argument, namely:

$$(k+1)V_{k+1}(z)=(2k+1+z)V_k(z)-kV_{k-1}(z),\quad k\geq 1 \tag{6}$$

and having the starting values:

$$V_0(z)=\int_z^{\infty}\frac{\exp(-u)}{u}du \qquad \text{and} \qquad V_1(z)=(1+z)\int_z^{\infty}\frac{\exp(-u)}{u}du-\exp(-z) \tag{7}.$$

3.4. Evapotranspiration

ET is a major component of the water budget in vegetated areas that have relatively shallow groundwater tables. Actual ET varies with depth to water table. The decline in ET due to lowering the water table is calculated according to the decay model proposed by Shah et al. (2007):

$$ET_a = \frac{ET}{PET} = 1 \qquad \text{for} \qquad d \le d' \tag{8a}$$

$$ET_a = \frac{ET}{PET} = e^{-b(d-d')} \qquad \text{for} \qquad d > d' \tag{8b}$$

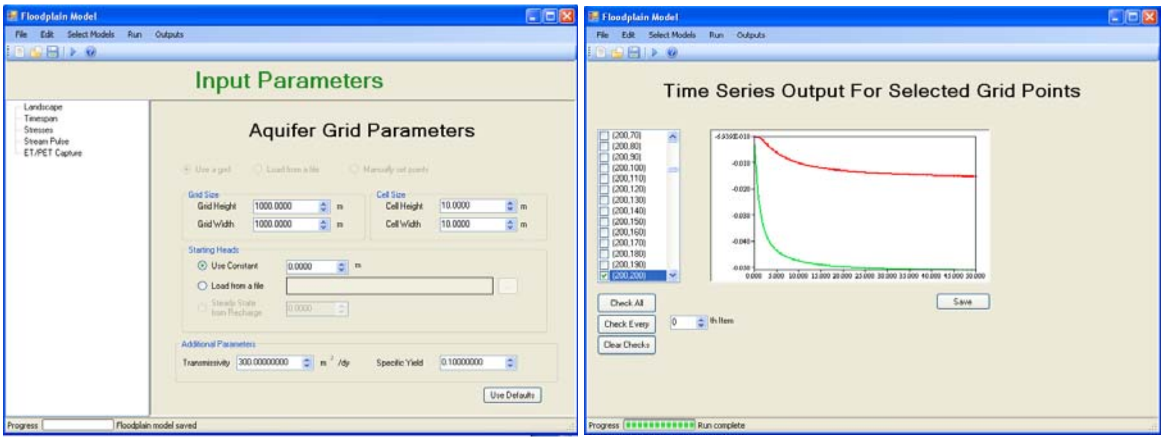
where PET is potential evapotranspiration, d is the depth to groundwater table, b is a decay coefficient, and d′ is known as the transition depth where ET shifts from atmospheric control to soil-moisture control. Parameters b and d′ vary with soil and land cover types (see Shah et al., 2007). The time series for actual ET is considered as a negative recharge source, and pressure heads and fluxes are calculated as described in Section 3.3.

4. SOFTWARE DEVELOMENT AND MODEL’S INPUTS/OUTPUTS

The Floodplain Model software is written in C# using components of the TIME libraries (Rahman et al 2003), purpose built C# classes, and user interfaces. The stand-alone version of the software has three main components: (1) the input component where the model input parameters are specified, (2) the execution component where the output state variables are specified, and (3) the output component where output type and display options are specified.

The input component of the stand-alone version of the Floodplain Model allows the user to enter the following input parameters (1) Aquifer Grid Parameters (see Figure 2A) - the unconfined aquifer is represented as a regular grid, bounded on one side by a river reach. When calculating changing heads over time the model calculates head values for each of the grid intersection points. The aquifer grid parameters are grid height, grid width, cell height, cell width and a starting head value for each grid line intersection point. Aquifer transmissivity and specific yield are also required. Figure 2A shows the Aquifer Grid Parameters form from the stand-alone version of the Floodplain Model; (2) Time Parameters - includes the start and end times for the simulation and the time step; (3) Stress Parameters - any number of stresses can be included simultaneously. Parameters for each stress are location, type (pump or recharge), start time, time step size, and a set of values which defines the signal associated with the stress; (4) Overbank Flow Events - the required input include: area of formed wetland, the distance from their centre to the river, and the volume of water available (5) Stream Pulse Parameters - A stream pulse defines the change in stream stage height representing a flood wave in the river; and (6) ET magnitude and ET model parameters.

The execution component allows the user to select which state variables they want to the model to calculate; they include pressure heads and river-aquifer exchange fluxes. The pressure heads are calculated at each grid intersection point at each time step. The fluxes to and from the river are integrated along its entire length, although the user can calculate fluxes for any length of the river reach if required.



Grid Size
Grid Height 1000.0000 m
Grid Width 1000.0000 m
Cell Size
Cell Height 10.0000 m
Cell Width 10.0000 m
Starting Heads
● Use Constant 0.0000 m
○ Load from a file
○ Steady State from Recharge 0.0000
Additional Parameters
Transmissivity 300.00000000 m^2/dy
Specific Yield 0.10000000
Progress Floodplain model saved

☐ (200,70)
☐ (200,80)
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Progress Run complete

Figure 2. Input and output screen captures from the Floodplain Model

The output component allows the user to view and save model outputs. The user is able to view, compare and save multiple time series of head values for any of the grid intersection points in the aquifer. For Fluxes, the user can view and save a time series of total fluxes for the entire river reach or a time series of fluxes for a particular section of the river; a sample output is shown in Figure 2A.

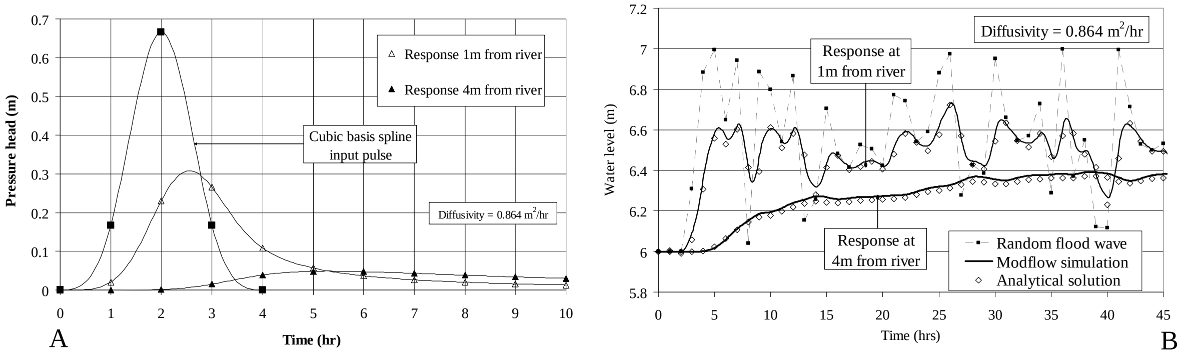

Figure 3. Predicted aquifer pressure heads during bank storage and comparison with MODFLOW simulation for arbitrary stage height time series

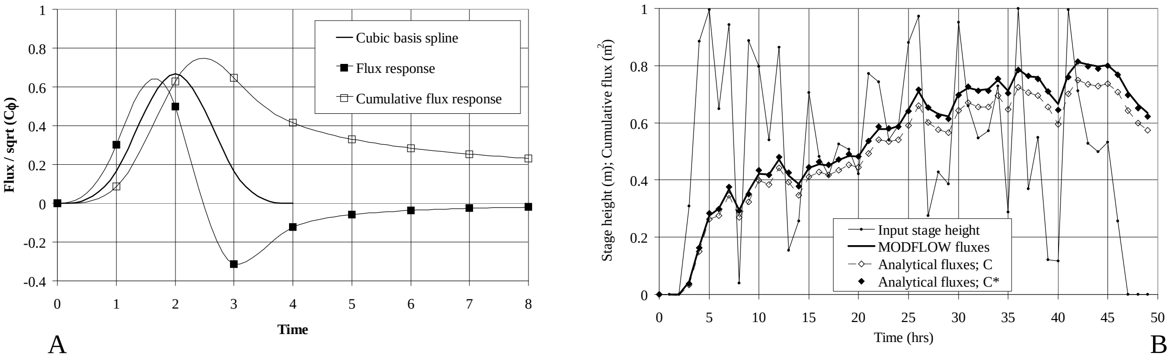

Figure 4. Predicted exchange fluxes during bank storage and comparison with MODFLOW simulation for arbitrary stage height time series

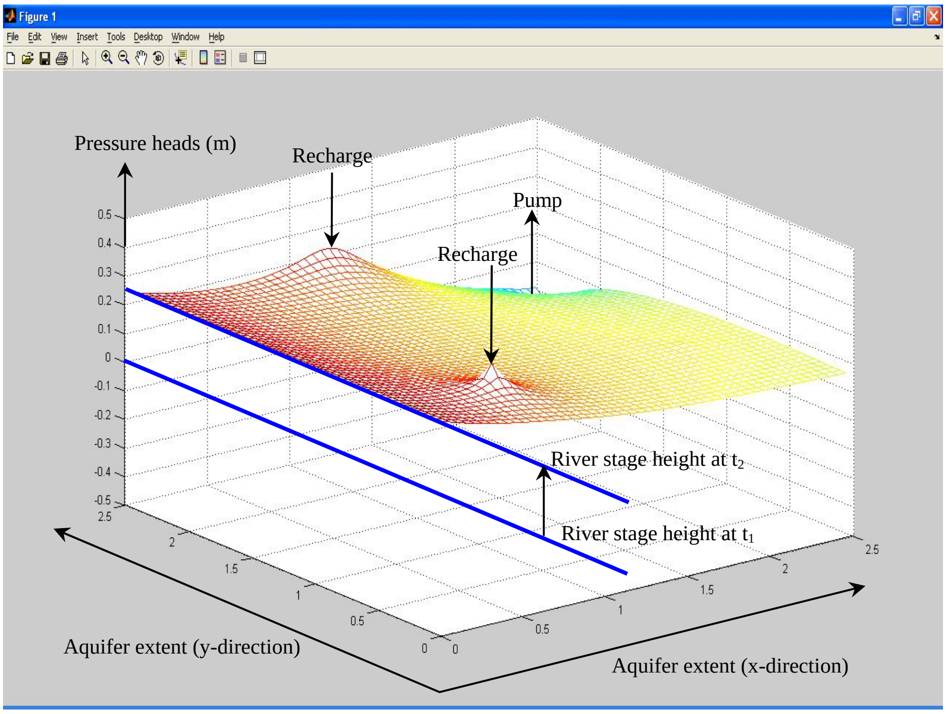

Figure 5. Two-dimensional representation of pressure heads in an aquifer due to the combined effects of change in river stage height, recharge, and pumping

5. RESULTS AND MODEL VALIDATION

Figure 3A shows a typical cubic basis spline pulse having the values of 0, 1/6, 2/3, 1/6, 0 at its respective five knots (knot spacing here is hourly). The spline here represents a time series of river stage heights (having those five values; this is our modular flood wave that we will use, along with numeric coefficients, to describe any arbitrary wave). This basis spline was used to describe the random time series for river stage heights (marked random flood wave) shown in Figure 3B. The aquifer pressure head responses at 1 and 4 m from the river due to the cubic basis spline stress are shown in Figure 3A; those are used, along with the same numeric coefficients used to fit the flood wave, to evaluate the pressure head response in the aquifer due to the arbitrary flood wave (see Figure 3B). Numerical simulations using the industry standard MODFLOW model (McDonald and Harbaugh (1988) showed that predictions obtained from the Floodplain Model are in close agreement with those obtained from the numerical model (see Figure 3B). Similarly, flux predictions from the Floodplain Model were found to be in close agreement with MODFLOW results (see Figure 4B).

Figure 5 shows a 3-dimensional plot of pressure head distribution in an aquifer where the combined impacts of a fluctuating river stage, a groundwater pump, and two recharge sources were combined. The 3-D plot was produced using a commercial software package based on output generated from the Floodplain Model.

6. CONCLUSIONS

The Floodplain Model is an intermediate complexity tool for modeling SW-GW interactions in floodplains. It dynamically models changes in pressure heads and exchange fluxes between an unconfined aquifer in hydraulic connection with a nearby river during randomly time-varying pumping, recharge, evapotranspiration, and river stage heights (including overbank flow). The performance of the underpinning analytical solutions has been tested against the industry-standard numerical model, MODFLOW whereby the model predictions were found to be in close agreement with the MODFOW predictions. The stand-alone version of the Floodplain Model is a powerful analytical tool for modeling floodplain processes. Future developments to incorporate this model into RiverManager will enable the latter to dynamically model SW-GW thus enhancing its capacity for better river management.

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