18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

A review of modelling of groundwater-surface water interactions in arid/semi-arid floodplains

Jolly, I.D.[1,3] **and D.W. Rassam**[2,3]

[1]*CSIRO Water for a Healthy Country National Research Flagship, South Australia*
Email: ian.jolly@csiro.au
[2]*CSIRO Water for a Healthy Country National Research Flagship, Queensland*
Email: david.rassam@csiro.au
[3]*eWater Cooperative Research Centre, Australian Capital Territory*

Abstract: Floodplains and their wetlands are extremely important centres of biodiversity due to their ability to support higher amounts of biomass than surrounding upland areas. This is as a result of flooding which provides greater availability of water and more dynamic nutrient cycling. In arid and semi-arid regions, where evapotranspiration is often much greater than rainfall, this additional source of water (and nutrients) creates ecological oases for many biota in what would otherwise be a harsh environment. Floodplains also have a very important hydrogeological role in that they are the interface zone between streams and groundwater systems where exchange of water and solutes occur between these systems. The groundwater systems of this interface zone are complex and dynamic with processes such as bank storage exchange, hyporheic zone exchange, overbank inundation and recharge, evapotranspiration and groundwater pumping needing to be accounted for in water balances. While modelling of groundwater-surface water interactions in floodplains, from either water resource availability or ecological sustainability perspectives, is far from a mature area of science, there have been significant advances over the last 15 years, particularly in the area of spatial modelling. In this paper, we summarise the advances that have been made in saturated zone, unsaturated zone and combined modelling methods.

Modelling has progressed from relatively simple 1D and 2D analytical and empirical approaches to highly sophisticated 3D spatially distributed integrated modelling systems, with the advances mirroring the vast increases in desktop computing power over that time. In our view, future advances in this discipline are not so much limited by either computing power or solution methods, but rather by the availability of suitable data needed to parameterize, calibrate and validate the current-day models. As pointed out by Silberstein (2003), any model is only as good as the data upon which it is based and has been tested. Whilst calibration of very detailed process models has been possible for small (sub-reach scale) study areas, success has been limited at the reach, catchment and regional scales. However, new large-scale satellite/airborne data acquisition techniques are showing great promise, with some of the recent studies illustrating their value in model parameterization, calibration and validation. Because of severe data limitations in many areas, simple analytical models are still an attractive option in many cases as they generally only have a small number of parameters that require calibration. They can also be easily incorporated into publically available (i.e. inexpensive non-proprietary) GIS and other software frameworks. In our view, use of more sophisticated numerical models are only valid in data-rich situations or when used as research tools to study fundamental processes and parameter dependencies. At best, most detailed models will be only be usable for management as forecasting/what-if tools, and should not be considered as scenario prediction models unless they have been thoroughly calibrated and validated.

Keywords: *Groundwater, surface water, interaction, floodplain, modelling*

1. INTRODUCTION

Approximately one third of the world's land area is comprised of arid/semi-arid regions (Rogers, 1981). Extreme climatic variability and subsequent hydrological fluctuations are typical in these regions. The climatic variability occurs seasonally, inter-annually and on longer time frames. Consequently, arid/semi-arid areas are subjected to frequent and severe droughts and infrequent but significant floods. Climate variability and subsequent fluctuating hydrology are key drivers of ecology in arid/semi-arid environments.

To overcome the highly variable stream flow in arid/semi-arid areas, rivers have been regulated to provide year-round water supplies, transportation, waste assimilation, recreation and electricity generation. River regulation has often had profound hydrological and ecological side-effects on the rivers themselves and their adjacent floodplains (Jolly, 1996). Floodplains generally support higher amounts of biomass, have greater primary production and more dynamic nutrient cycling than surrounding upland areas. This is particularly the case in arid/semi-arid areas where potential evapotranspiration is greater than rainfall for most months and so flooding provides an additional source of water not available to non-floodplain areas (Hollis, 1990). Floodplains often also have an important hydrogeological role as the interface zone between streams and groundwater systems where exchange of water and solutes occur. Groundwater systems of this zone are complex and dynamic, with processes such as hyporheic exchange, bank storage exchange, overbank inundation, evapotranspiration and groundwater pumping needing to be accounted for in water balances (see Figure 1 for examples of some of these processes).

There have been significant advances over the last 15 years in the modelling of groundwater-surface water interactions in floodplains (water and solutes), both from a water resource availability perspective and from an ecological sustainability viewpoint. It is timely to take stock of what has been achieved to predict future directions. This short paper summarises the advances made and discusses some of the data issues which are limiting further progress in this area. The paper builds on the findings of a recent review of groundwater-surface water interactions in arid/semi-arid wetlands (Jolly et al., 2008) by expanding the scope to floodplains in general and by focusing specifically on modelling approaches. We describe saturated zone, unsaturated zone and combined methods.

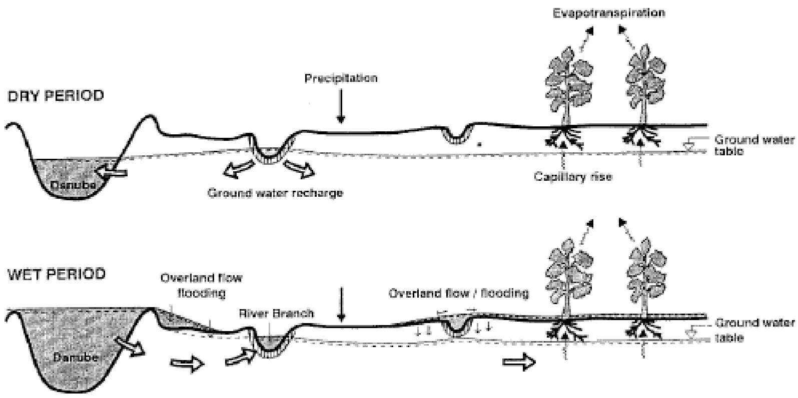

Figure 1. Important floodplain hydrology processes and their interactions (from Refsgaard et al., 1998).

2. SATURATED ZONE METHODS

2.1. Bank storage

By the early 1990's considerable literature had been developed on analytical solutions to bank storage interactions (see extensive review by Rassam and Werner, 2008). The first published application of these solutions to a arid/semi-arid floodplain situation was the study of Jolly et al. (1994) which developed a 2D analytical solution for the prediction of groundwater heads beneath two 2 km long cross-sections of a floodplain which was controlled by head fluctuations of streams on either side of the floodplain. This relatively simple model provided good transient predictions of groundwater head during a flood event on the Chowilla floodplain in south-eastern Australia. The main shortcomings of the approach were (i) that it assumed that Dupuit-Forchheimer conditions hold (i.e. horizontal groundwater flow); (ii) it only predicted groundwater heads and not fluxes; and (iii) it did not apply to situations where there was vertical recharge or discharge within the floodplain (i.e. only the effects of bank storage were modelled).

Whiting and Pomeranets (1997) also developed a general 2D model of bank storage (WaTab2D). This model used a finite element approach that enabled representation of the seepage faces that form on the sides of stream channels, non-symmetrical valleys, non-symmetrical channel banks, non-uniform hydraulic geometry (i.e. Dupuit-Forchheimer conditions do not need to hold), and non-zero boundary fluxes. The un-calibrated model was used to show that the total volume of water released from bank storage is nearly proportional to the width of the floodplain, the height of the bank, and the specific yield of the aquifer. It was also used to show that the duration over which water is released from bank storage (i) increases with floodplain width and decreases with hydraulic conductivity; (ii) the rate of release decreases in an exponential-like manner; and (iii) can occur over time periods ranging from days (in gravels) to years (in clays).

The most recent work on 2D floodplain bank storage methods is the analytical model of Knight and Rassam (2007). This is a significant improvement on previous analytical methods in that the stream head fluctuations can be a random time series (described using basis splines) rather than having to be represented in functional form or as a convolution interval which must be evaluated numerically. The value of using analytical approaches such as this is that they can be easily incorporated into geographical information system (GIS) models. For example, Rassam et al. (2008) used this new method within a GIS framework to study the nitrate attenuation potential of riparian zones in the large (60,000 ha) Maroochy catchment in eastern Australia (note that this case study was in a sub-tropical area, however the method has application to arid/semi-arid areas). This approach is also being employed in a new analytical/empirical floodplain model presently being developed by the eWater Cooperative Research Centre (see paper by Rassam et al., 2009).

2.2. Overbank inundation

The most notable modelling of overbank inundation in a system which has remained relatively natural is the recent studies of the very large (1,200,000 ha) Okavango Delta in Botswana. Bauer et al. (2004) showed that transpiration from arid/semi-arid floodplains such as the Delta can be significant in situations where water tables are shallow (< 5 m below ground) as floodplain vegetation can use groundwater as a supplementary water supply in dry periods between floods. This, along with evaporation from bare soils, can lead to accumulation of salt in plant root zones and in the underlying groundwater. Overbank flooding can mitigate these accumulations of salt. Wolski et al. (2006) developed a GIS-based hydrological model of the Delta which was able to establish an overall water budget and was used to map areas that are inundated from floods. Bauer et al. (2006a) carried out coupled 3D groundwater flow and salinity transport modelling of the 10,800 ha Shashe River Valley on the fringe of the Delta using a modified version of the density-dependent SEAWAT model (Guo and Langevin, 2002). In this valley, a fresh groundwater lens had developed naturally over time due to annual flooding, but was being heavily exploited for domestic water supply and by riparian vegetation, leading to declines in groundwater levels and deterioration of water quality due to ingress of saline groundwater from adjacent aquifers. The modelling was used to gain an understanding of the complex interactions, including the interdependence of groundwater salinity and riparian vegetation transpiration. The study successfully reproduced the development of the groundwater lens and recent decline in piezometric heads, as well as explaining the old age of the saline groundwater surrounding the lens. Zimmermann et al. (2006) investigated groundwater flow and salt transport dynamics below an evaporation-dominated island in the Delta with 2D density-dependent simulations using three different numerical models. The simulation results supported geophysical observations reported in Bauer et al. (2004) of density fingering (caused by downward convection of saline water) in the groundwater beneath the island. They also showed that these density effects may be entirely overridden by lateral flow if islands are imbedded in a sufficiently transmissive aquifer within a high regional hydraulic gradient. Wolski and Savenije (2006) also studied the dynamics of floodplain-island groundwater flow in the Delta, but employed more traditional MODFLOW modelling techniques. They found that floodplain-island groundwater flow was in general very dynamic, was driven by island evaporation and transpiration, and that regular flooding was required to replenish groundwater stores. They concluded that a prolonged reduction in the duration or level of a flood could result in depletion of the groundwater storage with negative effects on the riparian vegetation.

In many floodplain systems, river regulation by weirs/locks and upstream storages has led to raised water tables beneath floodplains and reduced frequency and duration of overbank flooding. Water tables beneath floodplains can also be raised by increased groundwater inflows into floodplains from adjacent areas due to changes in land management such as the development of irrigation areas. The increased evapotranspiration and decreased recharge that can result can lead to net accumulation of salt in plant root zones and consequent floodplain vegetation dieback (Jolly, 1996). Doble et al. (2006) used relationships for evapotranspiration response to groundwater depth and salt concentration, within the MODFLOW-2000 framework, to successfully model spatial patterns of groundwater flux and salt accumulation within a small (500 ha) floodplain in south-eastern Australia (Clarks Floodplain). To more accurately model the recharge and evapotranspiration processes in this floodplain environment, where the boundaries between recharging and nonrecharging cells change with time, Doble et al. (2009) modified the MODFLOW-2000 recharge (RCH) and segmented evapotranspiration (ETS) packages to produce a recharge-discharge function (CRD) that allows groundwater flux to be represented as a continuous process, dependent on water table depth.

Hyporheic exchange is the rapid movement of water from the stream channel into and out of the surface depths of the alluvial aquifer over short (sub-reach) distances. The importance of hyporheic exchange is that it keeps surface water in close contact with chemically reactive constituents and microbial colonies in the stream bed, thus enhancing biogeochemical reactions that influence downstream water quality and ecosystems (Harvey and Wagner, 2000). Over the last decade, there has been some progress in modeling these fine scale processes. The modeling has either been very site specific and based on finely-gridded groundwater models such as MODFLOW (e.g. Wroblicky et al., 1998; Poole et al., 2008) or has involved the development of analytical, numerical and/or statistical approaches to help understand some of the fundamental water and solute exchange processes (e.g. Qian et al., 2008;. Boano et al., 2008). Research on hyporheic processes in general is a very active area of current research.

3. UNSATURATED ZONE METHODS

As described above, evapotranspiration from floodplains can result in accumulation of salt in plant root zones which can be leached back into the groundwater system by overbank floods. Slavich et al. (1999a) modelled soil salt accumulation/leaching processes at 2 sites in the Chowilla floodplain using a 1D soil-vegetation-atmosphere-transfer model (WAVES) to assess possible management options such as increasing flooding frequency by release of water from upstream storages and groundwater pumping to lower the water table. Whilst the modelling was successful, the authors recommended that the management options needed to be evaluated further at the floodplain scale to be useful for management. Slavich (1999b) then developed a salinity index (WINDS-Index), related to vegetation health, which could potentially be used in a GIS framework to evaluate management options at the floodplain scale. The approach utilised a simple 1D analytical root zone salt and water balance model which represented the salinisation process as a moving salt front. The dominant features of the more detailed WAVES simulations were adequately reproduced, and the WINDS-Index was found to be strongly dependent on the relative flood inundation time (the ratio of the duration of inundation to the duration between floods) of successive flood events. Overton et al. (2006) then implemented the WINDS-Index approach spatially in a GIS framework, tested its predictions against vegetation health mapping, and successfully used it to assess a wide range of potential management options aimed at improving the vegetation health of the large (17,400 ha) Chowilla floodplain.

4. COMBINED SATURATED AND UNSATURATED ZONE METHODS

To account for variably saturated conditions within bank storage, and the effects of density due to large salinity contrasts between stream water and groundwater, Jolly et al. (1998) applied a variable density flow and solute transport model (SUTRA; Voss, 1984) to a 4 km long cross-section of the Chowilla floodplain. The model was used to assess the importance of overbank floods in the transport of salt from the floodplain groundwater system to the lower River Murray system. The simulations showed that the mixing of flood water and saline groundwater within bank storage could explain short-term (<12 months) salt load recessions, but the observed long term (12-24 months) salt load recessions were due to the groundwater impacts of localised recharge from overbank floods at some locations on the floodplain.

To study the environmental impacts of a hydropower scheme in the 130 km long Danubian Lowland in eastern Europe, Refsgaard et al. (1998) developed an integrated modelling system comprised of catchment (MIKE SHE; Refsgaard and Storm, 1995), river (MIKE 11 and MIKE 21; Havno et al., 1995 and DHI, 1995) and unsaturated zone (DAISY; Hansen et al., 1991) models. This coupling allowed detailed modelling of the dynamic hydrological regime of this area which captured the crucial links and feedback mechanisms between the various parts of the surface and sub-surface water regimes, in particular those of the floodplain. One of the issues with this study was that while it was possible to model a complex area such as this in great detail, and the individual models could generally be validated, only a few tests on the integrated model were possible. This highlights one of the key problems with very detailed process modelling; there are often insufficient data available to both parameterise the models and then calibrate and validate them.

Hammersmark et al. (2008) have also used MIKE SHE and MIKE 11 to model surface water-groundwater interactions, in this case to quantify the hydrological effects of stream restoration in a small (230 ha) montane meadow system in northern California. The system was small enough that sufficient data was collected to enable a very good calibration and validation of the models. As a result they were able to successfully evaluate the pre- and post- hydrological responses in the meadow to the ‘pond and plug’ restoration methods (alluvium excavated, forming ponds; excavated material used to plug incised channels; and smaller dimension channels restored to the floodplain surface level) commonly proposed for these systems.

Bauer et al. (2006b) developed a large-scale (1 km^2 grid) coupled 2D surface water-groundwater model to study the water balance of the entire Okavango Delta under a range of scenarios (increased water abstraction, development of upstream hydropower and irrigation schemes, channel dredging, local climatic change, local tectonic events). The model was comprised of components which simulate overland flow (based on a diffusive wave approximation of the 2D Saint-Venant equations), groundwater flow (based on a modified version of MODFLOW-96), and recharge and evapotranspiration through the unsaturated zone (using mass balance and an empirical relationship between evapotranspiration and water table depth). Due to a lack of site data, the model was not calibrated with point hydrographs but with pixel by pixel comparisons with flooding pattern time series derived from satellite imagery (151 images from 1972-2000). The authors cautioned that given the high uncertainty of both the calibrated and input parameters the model outputs could not be considered as predictions, rather they gave indications of the potential changes in flooding patterns.

There have also been extensive studies of a large (19,800 ha) floodplain of the Lower Havel River in northern Germany that have involved the development of the Integrated Modelling of Water Balance and Nutrient Dynamics (IWAN) modelling system (Krause and Bronstert, 2005, 2007; Krause et al., 2007a, 2007b). IWAN is comprised of the two way coupling (i.e. feedbacks in both directions) of the WASIM-ETH-I spatially distributed runoff generation and vertical soil water dynamics model (Schulla and Jasper, 1999) with MODFLOW-96. The most recent version of IWAN includes the SWIM (Krysanova et al., 2000) and MT3D (Zheng and Wang, 1999) models to simulate nitrate dynamics in both the unsaturated zone and groundwater (Krause et al., 2008). Use of IWAN to simulate the water balance of this floodplain indicated that interactions between groundwater and surface water controlled recharge dynamics in the floodplain and outweighed the influence of vertical percolation and root water uptake. While groundwater contributions represented only 1% of the annual total discharge of the river, in summer ~30% of the river flow was derived from groundwater discharge from the floodplain. Simulations of proposed land use and land management changes on the floodplain using IWAN showed that rates of nitrate leaching from the root zone into the groundwater and then the river could be reduced substantially, and this would have a large impact on river nitrate loads during low flow conditions.

5. CONCLUDING REMARKS

There have been very significant advances over the last 15 years in the modelling of groundwater-surface water-floodplain interactions. In addition to the studies described here there are at least a further 20 published studies focusing on temperate and tropical regions. Modelling has progressed from relatively simple 1D and 2D analytical and empirical approaches to highly sophisticated 3D spatially distributed integrated modelling systems, with advances mirroring the vast increases in desktop computing power over that time.

In our view future advances in this discipline are not so much limited by either computing power or solution methods, but rather by the availability of suitable data needed to parameterize, calibrate and validate the current-day models. As always, data collection is expensive, and therefore generally very difficult to fund. The scaling down of routine hydrological and hydrogeological monitoring in many jurisdictions has further exacerbated this problem. Many natural resource management policy makers and managers tend to consider process models as “silver bullets” without fully understanding that any model is only as good as the data upon which it is based and has been tested (Silberstein, 2003). Whilst calibration of very detailed process models has been possible for small (sub-reach scale) study areas (i.e. Hammersmark et al., 2008; Doble et al., 2006), success has been limited at the reach, catchment and regional scales. However, new large-scale satellite/airborne data acquisition techniques are showing great promise; the studies of Overton et al. (2006) and Bauer et al. (2006a) illustrate their value in model parameterization, calibration and validation.

In data-poor situations, simple analytical models are still an attractive option as they generally only have a small number of parameters that require calibration. They can also be easily incorporated into publically available (i.e. inexpensive non-proprietary) GIS and other software frameworks (e.g. Overton et al., 2006; Rassam et al., 2008, 2009). In our view, use of more sophisticated numerical models are only valid in data-rich situations or when used as research tools to study fundamental processes and parameter dependencies. At best, most detailed models will only be usable for management as forecasting/what-if tools, and should not be considered as scenario prediction models unless they have been thoroughly calibrated and validated.

ACKNOWLEDGMENTS

This review was funded by the eWater Cooperative Research Centre (and its partner agencies) and the National Water Commission Raising National Water Standards Program, under the Project "Australian Hydrological Modelling Initiative - Groundwater Surface Water Interaction Tool".

REFERENCES

Bauer, P., G. Thabeng, F. Stauffer, and W. Kinzelbach, (2004), Estimation of the evapotranspiration rate from diurnal groundwater level fluctuations in the Okavango Delta, Botswana. *Journal of Hydrology*, 288, 344-355.

Bauer, P., R.J. Held, S. Zimmermann, F. Linn, and W. Kinzelbach, (2006a), Coupled flow and transport modelling in semi-arid environments: The Shashe River Valley, Botswana. *Journal of Hydrology*, 316, 163-183.

Bauer, P., T. Gumbricht, and W. Kinzelbach, (2006b), A regional coupled surface water/groundwater model of the Okavango Delta, Botswana. *Water Resources Research*, 42, W04403, doi:10.1029/2005WR004234.

Boano, F., R. Revelli, and L. Ridolfi, (2008), Reduction of the hyporheic zone volume due to the stream-aquifer interaction. *Geophysical Research Letters*, 35, L09401, doi:10.1029/2008GL033554.

DHI (1995), MIKE 21 Short Description. Danish Hydraulic Institute, Horsholm.

Doble, R.C., C.T. Simmons, I.D. Jolly,. and G.R. Walker, (2006), Spatial relationships between vegetation cover and irrigation-induced groundwater discharge on a semi-arid floodplain, Australia. *Journal of. Hydrology*, 329, 75-97.

Doble, R.C. C.T Simmons, and G.R. Walker, (2009), using MODFLOW 2000 to model ET and recharge for shallow ground water problems. *Groundwater*, 47, 129-135.

Guo, W. and C.D. Langevin, (2002), User's Guide to SEAWAT: A Computer Program For Simulation of Three-Dimensional Variable Density Groundwater Flow. Techniques in Water Resources Investigations 06-A7, U.S. Geological Survey, Tallahassee.

Hammersmark, C.T., M.C.Rains, and J.F. Mount, (2008), Quantifying the hydrological effects of stream restoration in a montane meadow, northern California, USA. *River Research and Applications*, 24, 735-753.

Hansen, S., H.E. Jensen, N.E., Neilsen, and H. Svendsen, (1991), Simulation of nitrogen dynamics and biomass production in winter wheat using the Danish model DAISY. *Fertilizer Research*, 27, 245-259.

Harvey, J.W. and Wagner, B.J., (2000), Quantifying hydrologic interactions between streams and their subsurface hyporheic zones. In *Streams and Ground Waters* (Eds J.B. Jones and P.J. Mulholland), Academic Press, San Diego, pp. 3-44.

Havno, K., M.N. Madsen and J. Dorge, (1995), MIKE 11 – A Generalized River Modelling Package. In V.P. Singh (Ed), *Computer Models of Watershed Hydrology*, Water Resources Publications, pp. 733-782.

Hollis, G.E. (1990), Environmental impacts of development on wetlands in arid and semi-arid lands. *Hydrological Science*, 35, 411-428.

Jolly, I.D. (1996), The effects of river management on the hydrology and hydroecology of arid and semi-arid floodplains. In *Floodplain Processes* (Eds M.G. Anderson, D.E. walling and P.D. Bates), John Wiley and Sons, Chichester, pp. 577-609.

Jolly, I.D., G.R. Walker, and K.A. Narayan, (1994), Floodwater recharge processes in the Chowilla anabranch system, South-Australia. *Australian Journal of Soil Research*, 32, 417-435.

Jolly, I.D., K.A. Narayan, D. Armstrong, and G.R. Walker, G.R., (1998), The impact of flooding on modelling salt transport process to streams. *Environmental Modelling and Software*, 13, 87-104.

Jolly, I..D., K.L., McEwan, and K..L. Holland, (2008), A review of groundwater-surface water interactions in arid/semi-arid wetlands and the consequences of salinity for wetland ecology. *Ecohydrology*, 1, 43-58.

Knight, J.H. and D.W. Rassam, (2007), Groundwater head responses due to random stream stage fluctuations using basis splines. *Water Resources Research*, 43, W06501, doi:10.1029/2006WR005155.

Krause, S and A. Bronstert, (2005), An advanced approach for catchment delineation and water balance modelling within wetlands and floodplains. A*dvances in Geosciences*, 5, 1-5.

Krause, S. and A. Bronstert, (2007),. The impact of groundwater-surface water interactions on the water balance of a mesoscale lowland river catchment in northeastern Germany. *Hydrological Processes*, 21, 169-184.

Krause, S.; A., Bronstert, and E. Zehe, (2007a), Groundwater-surface water interactions in a north German lowland floodplain - Implications for the river discharge dynamics and riparian water balance. *Journal of Hydrology*, 347, 404-417.

Krause, S.; J. Jacobs, and A. Bronstert, (2007b), Modelling the impacts of land-use and drainage density on the water balance of a lowland-floodplain landscape in northeast Germany. *Ecological Modelling*, 200, 475-492.

Krause, S.; J. Jacobs, A. Voss, A. Bronstert, and E. Zehe, E., (2008), Assessing the impact of changes in landuse and management practices on the diffuse pollution and retention of nitrate in a riparian floodplain. *Science of the Total Environment*, 389, 149-164.

Krysanova, V., F. Wechsung, J. Arnold, R. Srinivasan, and J. Williams, (2000), SWIM (Soil and Water Integrated Model) User Manual. PIK Report No. 69. Potsdam Institute for Climate Impact Research, Potsdam.

Overton I.C., I.D. Jolly, P.G. Slavich, M.M. Lewis, and G.R. Walker, (2006), Modelling vegetation health from the interaction of saline groundwater and flooding on the Chowilla floodplain, South Australia. *Australian Journal of Botany*, 54, 207-220.

Poole, G.C., S.J. O'Daniel, K.L. Jones, W.W. Woessner, E.S. Bernhardt, A.M. Helton, J.A. Stanford, B.R. Boer, and T.J. Beechie, (2008), Hydrologic spiralling: The role of multiple interactive flow paths in stream ecosystems. *River Research and Applications*, 24, 1018-1031.

Qian, Q., V.R. Voller and H.G. Stefan, (2008), A vertical dispersion model for solute exchange induced by underflow and periodic hypoheic flow in a stream gravel bed. *Water Resources Research*, 44, W07422, doi:10.1029/2007WR006366.

Rassam, D.W. and A..D. Werner, (2008), Review of Groundwater–Surfacewater Interaction Modelling Approaches and Their Suitability for Australian Conditions. eWater Technical Report. eWater Cooperative Research Centre, Canberra.

Rassam, D.W., D.E. Pagendam, and H.M. Hunter, (2008), Conceptualisation and application of models for groundwater-surface water interactions and nitrate attenuation potential in riparian zones. *Environmental Modelling and Software*, 23, 859-875.

Rassam, D., T. Pickett, and J. Knight, (2009), The Floodplain Model. In Proceedings of 18th World IMACS/MODSIM Congress, Cairns, Australia, 13-17 July 2009.

Refsgaard, J.C. and B. Storm, (1995), MIKE SHE. In V.P. Singh (Ed), *Computer Models of Watershed Hydrology*, Water Resources Publications, pp. 809-846.

Refsgaard, J.C., H.R. Sorensen, I. Mucha, D. Rodak, Z. Hlavaty, L. Bansky, J. Klucovska, J. Topolska, J. Takac, V. Kosc, H.G. Enggrob, P. Engesgaard, J.K. Jensen, J. Fiselier, J., Griffioen, and S. Hansen, (1998), An integrated model for the Danubian Lowland - Methodology and applications. *Water Resources Management*, 12, 433-465.

Rogers, B.R. (1981), Fools rush in, Part 3: selected dryland areas of the world. *Arid Lands Newsletter*, 14, 24-24.

Schulla, J. and K. Jasper, (1999), Modellbeschreibung WASIM-ETH. Swiss Federal Institute of Technology (ETH), Zurich.

Silberstein, R. (2003), Why collect data when we can model it? In Proceedings of MODSIM 2003, Townsville, Australia, 14-17 July 2003, 915-920.

Slavich, P.G., G.R. Walker, I.D. Jolly, T.J. Hatton, and W.R. Dawes, (1999a), Dynamics of *Eucalyptus largiflorens* growth and water use in response to modified watertable and flooding regimes on a saline floodplain. *Agricultural Water Management*, 39, 245-264.

Slavich, P.G., G.R. Walker, and I.D. Jolly, (1999b), A flood history weighted index of average root-zone salinity for assessing flood impacts on health of vegetation on a saline floodplain. *Agricultural Water Management*, 39, 135-151.

Voss, C.I. (1984), SUTRA: A Finite-Element Simulation Model For Saturated-Unsaturated Fluid-Density-Dependent Groundwater Flow With Energy Transport or Chemically Reactive Species Solute Transport. Water Resources Investigations Report 84-4369, U.S. Geological Survey, Reston.

Werner A.D., M.R. Gallagher, and S.W. Weeks, (2006), Regional-scale fully coupled modelling of stream-aquifer interaction in a tropical catchment. *Journal of Hydrology*, 328, 497–510.

Whiting, P.J. and M.A. Pomeranets, (1997), Numerical study of bank storage and its contribution to streamflow. *Journal of Hydrology*, 202, 121-136.

Wolski, P. and H.H.G. Savenije, (2006), Dynamics of floodplain-island groundwater flow in the Okavango Delta, Botswana. *Journal of Hydrology*, 320, 283-301.

Wolski, P., H.H.G. Savenije, M. Murray-Hudson, and T. Gumbricht, (2006), Modelling of the flooding in the Okavango Delta, Botswana, using a hybrid reservoir-GIS model. *Journal of Hydrology*, 331, 58-72.

Wroblicky, G.J., M.E. Campana, H.M. Valett, and C.N. Dahm, (1998), Seasonal variation in surface-subsurface water exchange and lateral hyporheic area of two stream-aquifer systems. *Water Resources Research*, 34, 317-328.

Zheng, C and PP. Wang, (1999), MT3DMS: A Modular Three-Dimensional Multi-Species Transport Model For Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User’s Guide. Contract report SERDP-99-1, US Army Corps of Engineers Engineer Research and Development Center, Vicksburg.

Zimmermann, S., P. Bauer, R. Held, W. Kinzelbach, and J.H. Walther, (2006), Salt transport on islands in the Okavango Delta: Numerical investigations. *Advances in Water Resources*, 29, 11-29.