(Proc. of JS.1 at the Joint IAHS & IAH Convention, Hyderabad, India, September 2009). IAHS Publ. 328, 2009.

Enhanced groundwater modelling methods for analyses in ecohydrology

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Abstract Water operations policy to support improved habitat for riparian and aquatic species is being implemented in many regions of the United States. Habitat-motivated outcomes include surface and groundwater hydrology metrics. The desired hydrological outcomes include specific seasonal hydrographs to support spawning and other fish needs; and, overbank flooding or maintenance of shallow groundwater conditions to support native riparian vegetation, providing nesting habitat or serving other ecological functions. Success in achieving surface water and groundwater metrics is dependent on multiple concurrent interactions, not only between surface water and groundwater within the hydrogeological setting of the near-river zone, i.e. river gains and losses, but also on evapotranspiration, which varies by plant group, season, and depth to groundwater; and, on regional groundwater boundary conditions, which may be influenced by climate, urban, or irrigation demand. Finally, the river bed itself may undergo change under different flow regimes, and present further uncertainty in extrapolating from historic hydrological relationships to future conditions. To improve understanding of hydrological relationships in the near-river zone and assess impacts of water operation alternatives on ecology-based hydrological metrics, a modelling approach has been developed that incorporates transient processes that potentially impact groundwater conditions and groundwater–surface water interactions. This approach has been applied to the evaluation of river restoration and water operation alternatives on the Rio Grande in New Mexico and the San Joaquin River in California, USA. Very high-resolution three-dimensional groundwater models are employed, with the width and depth of wetted river channel and flooded overbank areas set as flow-dependent boundary conditions, obtained from a companion surface water routing model. To incorporate variable water demand by vegetation, riparian plant functional groups are identified that can be separately assigned potential evapotranspiration rates, seasonally-varying rates of water use, and rooting depths. External transient processes, such as regional water demand, that impact the near-river groundwater zone are specified according to a hypothesized future condition. Model simulations illustrate the sensitivity of desired hydrological metrics to other elements of the ecosystem, and demonstrate the need to evaluate possible future scenarios not against static assumptions drawn from past observed conditions, but in light of physically-based transient system dynamics.

Key words riparian; groundwater; ecohydrology; modelling; conjunctive use; New Mexico; California; San Joaquin; Rio Grande

INTRODUCTION

Water managers globally face growing challenges from limited supply, increasing demand, and competing uses, including urban, agricultural and environmental. Addressing these challenges, while maximizing beneficial water use, requires an increasingly sophisticated suite of tools. In the western United States, interest in maintaining the ecological function of rivers has grown considerably over the past several decades. In the past, many rivers were operated primarily to serve human water demand but this practice is no longer accepted by the public, nor is it supported by numerous legal mandates, including the Endangered Species Act. To maintain rivers capable of supporting both riparian and aquatic life while simultaneously extracting water for human use, characterization of near-river hydrological conditions that affect ecological function is critical. Understanding how changes in regional groundwater use, river morphology, and restoration or degradation of riparian communities will impact river flow and river gain/loss, thereby impacting not just aquatic and riparian community maintenance and health, but the ability to route and deliver water, is significantly aided by the development and application of near-river groundwater riparian models. Techniques of enhanced groundwater modelling to support analyses in ecohydrology, and their application to two river systems in the western United States, are described in this paper.

PHYSICAL PROCESSES AND MODELLING METHODOLOGY

Water requirements for aquatic life and riparian vegetation are complex. Desirable river and overbank hydrological conditions are often dependent on species, life stage, and season. Hydrologists look to ecologists to define the desired hydrological conditions, that is, the amount and timing of in-channel river flow; nature of wetted conditions and overbank flooding; and, persistence of saturated soil conditions or depth to groundwater. Hydrologists then must evaluate how the desired conditions might be achieved, given available reservoir storage, other inflows, river channel gains and losses, and other physical processes that affect the near-river environment. Hydrological conditions within the near-river environment are dynamic and depend on multiple factors. A riparian groundwater model can be helpful in characterizing these conditions if sufficient transient physical processes are simulated. The modelling methodology applied uses a well-known groundwater model code, MODFLOW 2000 (Harbaugh *et al.*, 2000), with special attention to resolution and to transient stresses in the near-river zone. The physical processes targeted in this approach include river losses varying with river stage and width; evapotranspiration; and, flux to and from the regional groundwater system. Together, these processes impact hydrological conditions important to ecological function in the near-river environment.

Width and depth of wetted river channel and flooded overbank areas

Rivers in the deserts of the southwest and western regions of the United States experience large fluctuations in flow throughout the year, and among years. Changes in flow are accompanied by changes in the depth and width of water in the river. In some environments, overbank flooding also occurs and has significant impact on the near-river groundwater environment. In order to capture this variability as a boundary condition on the groundwater model, a time-variable river condition is defined and simulated by using a set of MODFLOW River Packages (RIV Package), instead of a single RIV Package, to define the river condition. In this process, a separate RIV Package is constructed for each of a series of river flow conditions selected for simulation from a step-function approximation of the river hydrograph. The specified river conditions include, for each model cell traversed by the river, the elevation of the channel bottom, the elevation of the water surface in the channel, and a conductance term. This package is also used to specify characteristics of flooded overbank areas. The conductance term incorporates assumptions regarding vertical hydraulic conductivity, bed thickness, and the wetted area in the model cell.

An example of a two-year flow condition and its step-function approximation is given in Fig. 1. For each function step, the river width and extent is defined throughout the groundwater model

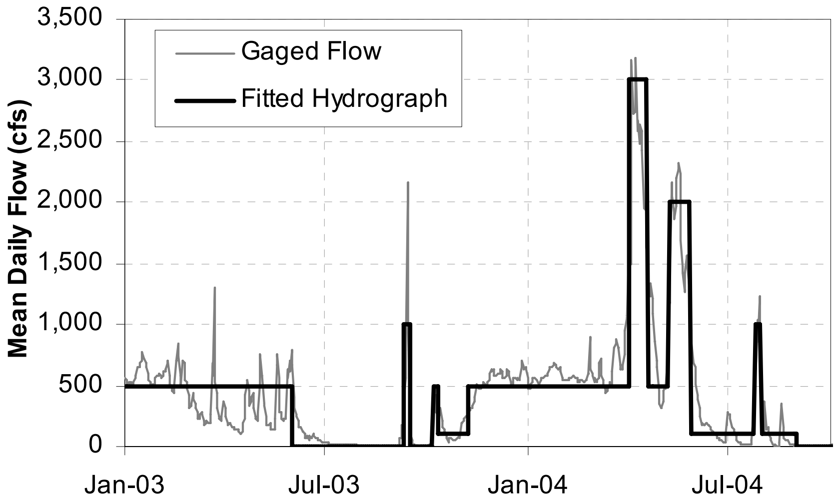

Fig. 1 Daily mean flow and a fitted step-function hydrograph used to identify flows for a suite of MODFLOW River Packages.

domain with a companion hydraulic model that provides this information either for discrete river cross-sections, or, through 2-D simulation of the river and overbank areas. To simulate the hydrograph shown in Fig. 1, 14 flow levels are identified and used as a basis for 14 RIV Packages that are sequenced in the transient model simulation. In this process, model stress periods are defined to correspond to the steps of the step-function hydrograph. This approach captures the high variability of river and overbank conditions that impact river gain/loss rates and depth to shallow groundwater.

Evapotranspiration

To incorporate variable water demand by vegetation, riparian plant functional groups are identified from high-resolution aerial photographs. For each plant functional group, evapotranspiration rate curves, which vary with both depth to groundwater and season, are developed. The resulting riparian vegetation representation is highly responsive, both spatially and temporally, to changes in local and regional groundwater conditions.

Regional groundwater conditions

Regional groundwater conditions are specified as a boundary on the near-river zone using the MODFLOW General Head Boundary Package (GHB Package). Application of the regional groundwater condition requires some assessment of the nature of changes expected in a given model simulation. If boundary conditions are expected to remain relatively static in comparison to the changes along the river, for some problems, static handling may be reasonable. In other cases, particularly a simulation of a multi-annual period, static handling may not be advisable. In the work described herein, changes to regional groundwater boundary conditions and their significance were evaluated through sensitivity analyses and altered for future simulations according to scenario assumptions. The specification of regional groundwater boundary conditions may be based on observations, i.e. water table maps corresponding to a condition of interest; or, from companion simulation with a regional groundwater model. In some cases, it may be desirable to integrate the regional groundwater model and the near-river riparian model to attain a fully linked system. However, as a practical matter, this is not always necessary nor worth the time and effort, depending on the nature of the problem to be solved.

Model domain and model discretization

Modelling near-river hydrological conditions requires that the modelled area, or domain, extends over the length of the river reach of interest and over a width that includes, at a minimum, the river flood plain. Ideally, lateral boundaries for the model are located beyond the flood plain in an area with significant hydrogeological contrast, or, are coincident with hydraulic features such as riverside drains. The model domain is frequently defined by an alluvial setting, inset within a regional aquifer of lower transmissivity. In the case studies described below, the areas of interest and model domains extend from 50 to 150 river miles in length and up to one mile in width. River alluvium is typically a few tens to a couple hundred feet in depth. High-resolution discretization of the model domain is desirable, to support detail in specifying river and vegetative conditions. Model cells may be specified, for example, as 100 × 200 feet (30.5 × 71 m) in size; and multiple model layers may be needed to capture vertical head conditions.

Specification of land surface and channel elevations

Accurate representation of land surface, river channel bed, and river stage elevations is important. Groundwater elevations in the near-river environment may be controlled by river elevations, by regional groundwater conditions, and, if present, by water elevations and channel bottom elevations in bounding drains or canals. If the elevations associated with these features are not accurate, model results will reflect these inaccuracies. For the applications here, river channel bed and riverside drain elevations are based on available survey data. Survey data are reviewed for datum consistency both between surveys, and with respect to the land surface elevations.

Land surface elevations are based on 1-m DTM data and 10-m DEM data, averaged to grid resolution. If a cell contains significant topographic variability and the average elevation does not reflect the elevation controlling key hydrological processes, some adjustment may be needed. For example, if a bridge crosses a cell, DEM points reflecting this feature should be excluded if evapotranspiration in the overbank is a significant process. Inaccuracy in DTM or DEM data can be problematic; thus, knowledge of metadata and the underlying accuracy of data are important, as well as the method of calculating average cell elevations. Inaccuracy in the land surface elevation will not necessarily invalidate results; however, this will complicate both representation of riparian evapotranspiration, and interpretation of results. For example, if river and boundary elevations are based on recent survey data and known to be relatively accurate, but land surface elevation data is poor, riparian evapotranspiration with depth curves will have to be revised to reflect estimated land surface elevation inaccuracies, and models results will have to be presented with respect to elevation, not referenced to land surface.

Calibration and data needs

Accurate calibration is best accomplished using both groundwater elevation and seepage data. Ideally, groundwater elevation data from multiple depths and across multiple cross-sections will be collected for a period spanning high and low flow river events. This allows calibration of both vertical and horizontal flow gradients at multiple points along the model. These data are relatively inexpensive to collect due to the shallow completions required for wells in a near-river alluvial environment.

Field collection of river flow at a sequence of locations, suitable for computing river gains or losses by mass balance methods (seepage runs), is recommended to obtain target observations of flux. Seepage results are not to be interpreted as static observations, rather, as dependent on conditions. However, coupled with contemporaneous observed groundwater elevations, seepage results are extremely useful in model calibration. Calibration is straightforward when both elevation data for model construction and calibration data are plentiful and accurate. As data quality and/or availability decline, model calibration is, of necessity, less constrained.

APPLICATION OF RIPARIAN GROUNDWATER MODELS ON TWO RIVERS IN THE UNITED STATES

San Joaquin River

Efforts are underway to evaluate and implement actions to restore 150 miles (240 km) of the San Joaquin River downstream of Friant Dam, in central California, with a view to re-introducing spring- and autumn-run Chinook salmon. This includes augmentation of river flows to achieve restoration hydrographs that vary in shape and volume according to a degree of “wetness” or, water year type, reflecting the basin water supply. In 1999, the need for a tool to assess the mechanism of river losses/gains and groundwater conditions under various flow regimes was identified by a stakeholder group. Five high-resolution, contiguous groundwater flow models, Fig. 2, were developed for this programme (SSPA, 2000; Hathaway, 2005) to qualitatively explore the hydrological dynamics that occur within the riparian zone in response to changes in both river flow and regional groundwater conditions.

Rio Grande Riparian Models

The Rio Grande in central New Mexico provides water to a significant portion of the New Mexico population, to over 50 000 acres of irrigated farm land, and to a river corridor that is home to both an endangered fish and an endangered riparian bird. This same river corridor is also the conduit for downstream interstate and international water deliveries. Numerous long-term projects, including several modelling studies, have improved our understanding of hydrological conditions in this reach, with the exception of the capability of these models to address conditions in the shallow groundwater corridor along the river. To address this gap, between 2003 and 2008, a series of eight contiguous, fine-mesh, 3-D groundwater models for the shallow riparian environment along the Rio Grande in central New Mexico was developed to support analysis of restoration options and river management strategies. The models, shown in Fig. 3, span approximately 180 river miles (290 km) from Cochiti Dam in the north to Elephant Butte Reservoir in the south.

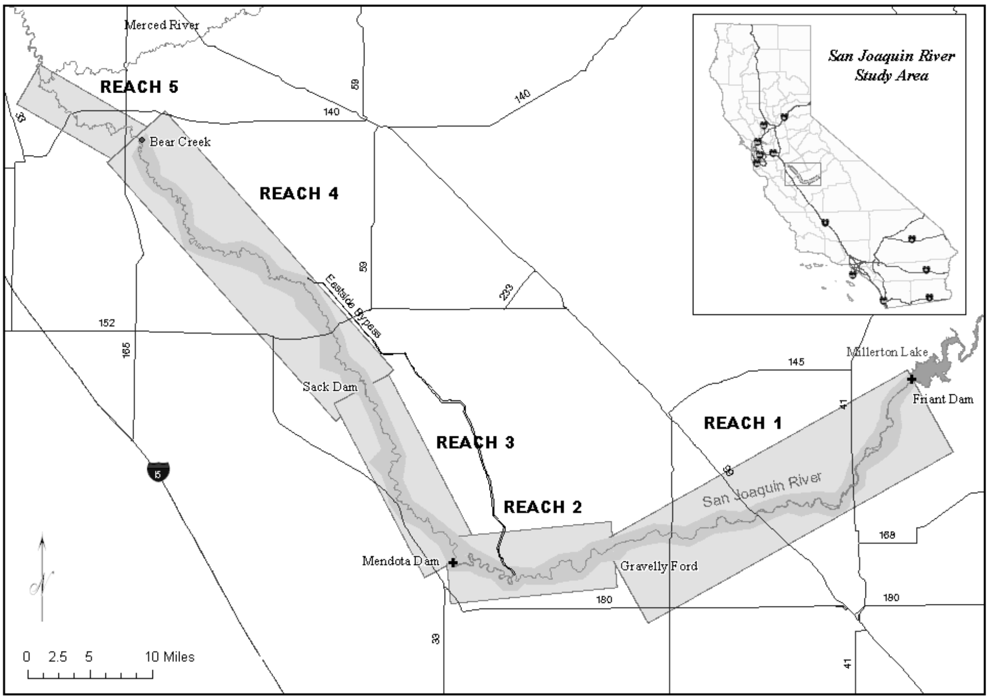

Fig. 2 Location of San Joaquin River Riparian Groundwater Models.

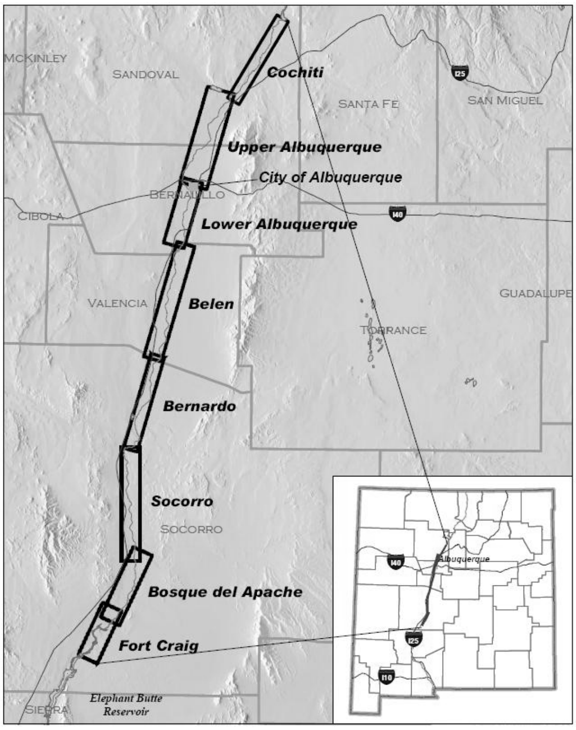

Fig. 3 Location of Rio Grande Riparian Models.

Model construction

Though differing slightly in their particulars, both the San Joaquin and Rio Grande riparian groundwater models are multi-layer, fine-mesh models designed to represent shallow near-river groundwater/surface water interactions, including riparian evapotranspiration. Both sets of models are developed in MODFLOW 2000, and both utilize output from existing surface water models to develop a suite of river conditions, represented in the RIV Package, for use in simulating changes in the hydrograph as defined with the step-function approximation.

The San Joaquin River riparian groundwater models utilize model cells 300 × 50 ft (91.44 × 15.24 m) in size; the shallow groundwater within about one half mile (800 m) to each side of the river is modelled in multiple layers, with boundary conditions specified to reflect deeper aquifer conditions and lateral regional boundary conditions. River boundary conditions are specified using HEC-2 (USACOE, 1990) model-generated water surface profiles. Evapotranspiration rates have been assigned based on general classifications of riparian communities mapped from aerial photographs. Evaporation rates have been assigned to each general class, or zone, using a class multiplier and a potential evaporation rate for the time frame of interest.

The Rio Grande riparian groundwater models utilize a uniform 4-layer grid, with grid cells measuring 250 × 125 ft (76.2 × 38.1 m). Modelled interactions include seepage from the river, interception of shallow groundwater by riverside drains, recharge to shallow groundwater from flooded overbank areas, and water depletions due to open water evaporation and riparian evapotranspiration. River boundary conditions are specified using FLO-2D (Tetra Tech, 2004) model-generated water depth and river coverage data. Regional boundary conditions are set along the riparian model edges: in the top layer, water depth in bordering riverside drains provides bounding conditions; in deeper layers, bounding conditions are based on heads extracted from available regional groundwater models. Riparian evapotranspiration rates are variable by plant, season and water table depth; riparian plant coverage is specified using existing mapped vegetation classifications.

MODEL RESULTS

Both the San Joaquin and Rio Grande riparian groundwater models have been used to quantify groundwater/surface water exchanges and to characterize shallow groundwater depths at high spatial and temporal resolutions in the near-river region.

Sensitivity of San Joaquin Riparian zone conditions to regional groundwater elevations and river operations

Three preliminary model simulations were made using the San Joaquin riparian groundwater models to evaluate the sensitivity of riparian zone conditions to regional groundwater levels and to river operations (S.S. Papadopulos & Associates, Inc., 2000). For these simulations, three conditions were defined for the regional boundary condition and for the river condition, each representing a low, medium or high range condition. Combinations of these conditions were evaluated for each reach to illustrate the sensitivity of riparian groundwater conditions to variation in these parameters. These analyses are briefly summarized below:

- *Alternate river flow conditions*: A change in river conditions had a significant impact on simulated groundwater levels. In some cases, the low flow scenario resulted in hydraulic disconnection of a previously connected channel and in significant dewatering of the shallow riparian zone. Conversely, the high flow scenario resulted in shallow water depths across a significant area of the riparian zone. Seepage rates under alternate flow conditions varied significantly, and these differences varied widely by reach.
- *Alternate antecedent river conditions*: Seepage rates for a given hydrograph are impacted by antecedent river conditions and corresponding groundwater levels. The sensitivity of seepage to antecedent flow conditions depends on reach lithology and other factors. The persistence of

this sensitivity is dependent on the antecedent and subsequent flow magnitude: for example, a high peak flow of extended duration may "erase" the antecedent condition effect, but, a short-duration flow peak will incur greater-than-expected losses if it follows a below-average period.

– *Alternate river boundary conditions*: A change in the representation of regional groundwater levels at the model boundary, within ranges seen over recent years, can change seepage rates by a factor of 2; in some sub-reaches, regional boundary condition changes can shift river sub-reaches from gaining to losing conditions. The sensitivity of riparian zone water levels and seepage rates to changes in regional boundary conditions is more pronounced under low flow conditions, when less water is available to recharge and maintain head conditions in the riparian zone.

Sensitivity of Rio Grande Riparian Zone conditions to regional groundwater elevations and river operations

The Rio Grande riparian groundwater models were used to evaluate hypotheses regarding potential conditions within and surrounding the riparian groundwater zone and to illustrate how water levels and river seepage rates are affected under different circumstances, including alternate vegetation, regional water level, and antecedent water supply conditions. These results provide insight into riparian zone responses that may be important to water management and river restoration actions. Results are briefly described below:

– *Alternate riparian vegetation*: It was assumed that existing riparian vegetation was replaced with alternative plant communities using 25% less water. Given the assumed distribution of riparian vegetation classes and associated rates for the modelled regions, the simulated groundwater elevation difference ranged from 0 to 2.5 feet (0 to 0.76 m), with elevated groundwater under the alternate vegetation assumption. Under the alternative vegetation assumption, both river seepage loss and water lost to ET was reduced; however, impacts were most noticeable in areas where higher-ET vegetation classes were concentrated, with little impact outside areas of vegetation change.

– *Alternate regional groundwater conditions*: Model boundaries were adjusted from the base case to represent modified, hypothetical regional groundwater and drain boundary elevations. Under the lower regional condition assumptions, the riparian corridor was significantly "drier" and increased river seepage rates occurred, although the degree of change was variable by model reach and by season. A drier corridor would impact the maintenance of target river flows for habitat, particularly in low flow periods; also, greater losses throughout the season would have impacts on water delivery via the river channel.

– *Alternate antecedent conditions*: Assumptions were made regarding river flows that might typify a low or high supply antecedent period, i.e. a period of several years drought or above-average supply. As simulated in this scenario, the impact of the antecedent condition was evident only immediately following the condition, and was minimal following the spring runoff. However, in practice, low antecedent flow conditions will likely result in altered boundary conditions. The degree to which boundary conditions are altered, how persistent the boundary conditions are during and following the spring event, and the magnitude and duration of the spring runoff, will work in concert to determine the full impact of antecedent conditions.

Evaluation of water operations and restoration scenarios

These models have been applied to evaluate seepage losses associated with various hypothetical or proposed restoration hydrographs under alternate regional groundwater and antecedent river flow assumptions. For example, for the San Joaquin models, among various restoration hydrographs considered, channel seepage losses ranging from 62 000 to over 144 000 acre-feet year^{-1} (7.65E^{7} to over 1.78E^{8} m^{3} year^{-1}) have been calculated, with differences attributable to the magnitude and duration of flow, previous year conditions, and regional groundwater condition assumptions. Greater variability is seen on a shorter time scale; for example, very high losses are observed for high flow peaks of durations less than a week, particularly when occurring during a dry period. The models have also provided mapped depths to groundwater under varied seasonal and operational conditions. These results provide information on areas of saturation that may be favourable for riparian vegetation, or that may cause detrimental water logging problems to agricultural interests.

IMPLICATIONS FOR WATER MANAGEMENT

Both the San Joaquin and Rio Grande riparian models provide a tool to assess river losses/gains and groundwater conditions under alternate flow regimes, within the backdrop of regional land use and water development conditions. The primary insight derived from the simulations is that the riparian environment is a dynamic environment impacted by multiple processes that manifest differently under different conditions, with inter-relationships among environmental components including groundwater, surface water and vegetation. These dynamics have implications for both river restoration and water operations, and provide the basis for understanding seasonal changes in seepage rates and shallow groundwater conditions that may be critical to the success of a river or bosque restoration project or change to water operations.

The riparian models can be used in a number of ways to support river restoration activities, including:

- *Site selection/assessment*: Simulations can be conducted to assess general characteristics, for example, anticipated ranges of river seepage under various operations, or maintenance of desired shallow groundwater conditions in the riparian zone.
- *Feasibility studies*: Alternate restoration approaches can be simulated and assessed to identify whether the project is likely to achieve hydrological objectives under an expected range of potential climate and water supply conditions.
- *Project design*: Projects that have been selected for design and construction can be modelled to fine-tune design elements.
- *Project monitoring and operations/maintenance*: Hydrological data pertaining to a project can be monitored and used to refine model characteristics for the project area. Then, change under forecasted or potential future conditions can be simulated, possibly providing an opportunity to identify and implement additional project controls to improve project success.

Through this progression, model development and refinement should be supported with increasing levels of locally relevant data.

The riparian models also have utility in evaluating water operations options for efficient conveyance of water to meet demands, whether the demand is driven by urban, agricultural, environmental or interstate compact needs. The efficient conveyance of water requires knowledge of river loss/gain under alternative supply, regional, and routing conditions. While river loss/gain can be quantified through field investigation, it would be impractical and expensive to conduct enough field investigations to characterize the losses/gains under all potential conditions that may be important to water management. The ability to transfer knowledge gained under one set of conditions to another set of conditions can be rapidly assessed using these modelling tools.

Hydrological conditions in the riparian zone occur at the interface between the surface water, groundwater, atmospheric, and biological domains – accurate assessment of conditions in the riparian zone requires consideration of dynamic exchanges between these four domains. Model simulations illustrate the sensitivity of hydrological conditions to other elements of the ecosystem, and demonstrate the need to evaluate possible future scenarios not against static assumptions drawn from past observed conditions, but in light of physically-based transient system dynamics.

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