Guidelines for modelling groundwater-surface water interactions in eWater Source

Towards best practice model application

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1 Introduction

1.1 Background

In many river systems, the extraction of large volumes of groundwater in close proximity to major streams and rivers has the potential to reduce stream flows. Basin-scale prediction tools that simulate these complex groundwater-surface water (GW-SW) interactions are required to assist in providing sustainable allocation of water. In un-regulated upland streams, the primary impacts are on low-flow conditions that are crucial to ecosystem health. In regulated rivers, the primary impacts are on water security as the rivers interact with the underlying groundwater system in a spatially and temporally varying manner. This interaction can be a gain to the river or loss from the river; the latter is considered an important source of recharge to the groundwater aquifer. In some situations there may be instances where the same parcel of water is allocated to more than one water user (i.e. double allocation).

The eWater CRC is developing eWater Source, an integrated modelling system which is the next generation of software tools for river planning, management and operation. As part of this effort, the eWater/National Water Commission ‘Groundwater Surface Water Interaction Tool (GSWIT)’ project has developed modules that provide GW-SW interaction capability for Source (Jolly et al., 2010).

One of the key challenges in modelling GW-SW interactions is the significant time-scale differences between surface water and groundwater processes. Because groundwater movement can be orders of magnitude slower than surface water movement, the responses of groundwater systems to hydrological and management drivers such as climate variability, land use change, and groundwater extraction can be very damped and lagged. Hence, a key requirement in modelling GW-SW interactions in river system models is to account for these time lags.

The modelling of GW-SW interactions in river system models is still very much in its infancy, not just in Australia, but also throughout the world. As such, there is no consensus on implementation of this functionality in river system models, and hence the little discussion in the literature so far on what constitutes Best Practice Modelling in this domain.

1.2 Scope

This document – hereafter referred to as “this guidance” – has been prepared by eWater as a first attempt at providing guidance on the application of GW-SW interactions in existing river and groundwater models, and in the new Source modelling tools incorporating GW-SW functionality. It is based on a combination of a literature review (Rassam and Werner, 2008), lessons learnt from the recent Murray-Darling Basin Sustainable Yield (MDBSY) project (Rassam et al., 2008), and lessons learnt during the development of the GW-SW functionality in Source (Rassam, 2011) and testing this functionality in trial reaches in the Namoi River basin.
The target audience for this document is practising river system and catchment modellers with an appropriate background who are interested in incorporating GW-SW interactions in their river planning models, i.e. it is not a text book.

This guidance is one of a series of Best Practice Modelling that has been prepared by eWater for each of the major functionalities of Source (Welsh et al., 2011). The overarching Best Practice Modelling framework for this series of documents is eWater’s Guidelines for Water Management Modelling (Black et al., 2011). These propose a high level generic procedure that is intended to result in quality assured model applications. The overall decision framework in the generic guidelines is illustrated in Figure 1.

![Figure 1: Decision framework for model application (Black et al., 2011)](image)

The generic guidelines describe a procedure for quality assured model application which can be summarised as comprising four phases:

1. Project management,
2. Problem definition,
3. Option modelling,
4. Compare options and select the best.

This guidance deals mainly with phases 2 and 3. From the point of view of application of GW-SW interaction modelling in Source the generic guidelines mostly provide sufficient information relevant to phases 1 and 4, particularly as GW-SW interaction modelling usually comprises part of a larger project and phases 1 and 4 would be covered in more detail in the planning and undertaking of this larger project.
2 Procedure for Quality Assured Application

The generic procedure proposed in Black et al. (2011) for quality assured model application is adapted from Blackmore et al. (2009) and is summarised in Figure 2. Please note that the procedure is flexible and should be tailored to the particular modelling project at hand.

For brevity, many sections in Chapter of this guidance simply refer the reader to the equivalent sections of the generic guidelines in order to avoid repetition of material.

![Flow chart of the procedure for quality assured model application](Figure 2)

2.1 Project administration

All the guidance on project administration in the generic guidelines applies to the implementation of GW-SW interaction modelling in Source, and no additional guidance needs to be provided here.
2.2 Problem definition

All the guidance on the Problem Definition phase in the generic guidelines is relevant to modelling GW-SW interactions. Additional to this, guidance specific to modelling GW-SW interactions is provided on the following topics in the sections below:

- Problem statement,
- Metrics and criteria, and
- Uncertainty and risk.

In relation to GW-SW interactions specifically, it is implicitly assumed that the work is concerned with implementing a catchment or river model where the river is in saturated connection with an underlying groundwater system, and that groundwater exchange is thought to be an important component of the river water balance. For the saturated connection, a range of processes impact the GW-SW exchange flux such as bank storage, groundwater extraction, evapotranspiration, and recharge. If the underlying groundwater is too deep to be in saturated connection then the process is restricted to surface water loss to the underlying aquifer (river recharge). The depth of the water table at which a river system becomes disconnected from the underlying groundwater system can be theoretically evaluated according to the criteria proposed by Brunner et al. (2009). Details on the experimental methods for assessing the state of connection between rivers and aquifers are found in Brownbill et al. (2011).

Problem statement

Extensive analyses should be conducted to justify the need for a new model to estimate the GW-SW exchange fluxes. For example, if good quality groundwater head data is available in close proximity to the river reach of interest, and the period and frequency of the groundwater data record correspond to those of the river model calibration/prediction period, then the fluxes can be calculated using Darcy’s Law (see Equation 2 of the Groundwater chapter of the Source Scientific Reference Guide; eWater, in press).

Alternatively, a groundwater model that encompasses the reaches of interest might be available. In such cases, the GW-SW exchange fluxes predicted by the groundwater model can be imported into the river model. However, prior to this process, one needs to ensure that the groundwater model satisfies some critical criteria. Firstly, the calibration period and the time steps of the groundwater model need to correspond to those of the river model. Secondly, the groundwater model has been purpose-built to provide reliable predictions for GW-SW exchange fluxes; for example, one of the crucial requirements is a suitable boundary condition such as the River boundary in MODFLOW. Note that due to the dependence of the GW-SW exchange fluxes on the river stage height, it may be necessary to calibrate the groundwater and river models simultaneously; this implicitly means that this is an iterative process (see Section 2.3.4 below).

Metrics & criteria

Where model calibration is part of the scope of work, consideration should be given to how good a model calibration needs to be, and which aspects of model performance are of greatest interest; these should feature in calibration metrics. Middelmis (2000) and Hill and Tiedeman (2007) discuss relevant calibration metrics for groundwater modelling. After
Guidelines for groundwater–surface water interactions modelling

achieving a satisfactory calibration, one needs to assess the quality of the model predictions and the associated uncertainty. Further guidance on this topic is available in the subsection on metrics and criteria in the Problem Definition phase section, in Chapter 2 of the generic guidelines.

Uncertainty and risk

Much of the subsection on uncertainty and risk in the Problem Definition phase section, in Chapter 2 of the generic guidelines is in principle relevant to the implementation of GW-SW interaction modelling in Source. However, work on model uncertainty and decision frameworks (e.g. CREM, 2008; Blackmore et al., 2009) has not been tested in the groundwater domain. While Hill and Tiedeman (2007) have extensive discussion on methodologies for assessing parameter and predictive uncertainty, the highly mathematical nature of the subject has resulted in only minimal uptake of the techniques by groundwater modellers in Australia. The more recent work by Doherty (2010) and Doherty et al. (2011) provide a good insight on this topic.

Development of practical, easy to use, uncertainty and risk techniques for GW-SW interaction modelling is clearly an area of future research, but is outside the scope of eWater. CSIRO has recently commenced a study based in the Namoi River basin on this research topic (see Lerat et al., 2011).

2.3 Option modelling

The guidance on option modelling in the generic guidelines is relevant to modelling GW-SW interactions except the guidance on uncertainty analysis, which is only partly relevant for reasons discussed in Section 0. Additional guidance specific to modelling GW-SW interactions is provided on the following steps in the sections below:

• Methodology development,
• Calibrate model, and
• Sensitivity/uncertainty analysis.

Methodology development

A key requirement for modelling GW-SW exchange fluxes is accounting for the time lags associated with groundwater processes that are much slower than those of surface water. Moreover, the hydraulic connection between a river and the underlying aquifer (as informed by connectivity mapping) can either be saturated or unsaturated depending on the location of the water table relative to the river stage.

The GW-SW exchange flux comprises four components:

1 natural exchange flux resulting from river stage fluctuations during low flow conditions, within bank and overbank fluctuations;
2 flux due to groundwater extraction;
3 flux due to changes in aquifer recharge; and
4 flux due to changes in evapotranspiration.
The sum of those components at any time dictates whether the river loses water to or gains water from the aquifer. A detailed description of the processes that actively contribute to the flux and that contribution varies with the type of river-aquifer connection is found in Rassam (2011).

The GW-SW exchange flux can be determined using one of the following methods, depending on data and model availability:

**Head-Based Method:** From knowledge of the head difference between the river stage and the water table level in the underlying aquifer at any time, the GW-SW exchange flux can be defined by multiplying the head difference by the hydraulic conductance of the river-aquifer interconnection (see Equation 2 in the Groundwater section of the Source Scientific Reference Guide; eWater, in press). The head difference at any time T captures the state of connection between the river and the underlying aquifer and hence represents a realisation of all the stresses in the aquifer up to that particular time T. The advantage of this method is that the flux calculations can start and finish at any time thus coinciding with the simulation (or calibration) period of the river model; this is conceptually correct because of the transient nature of the data. However, the limitation of this method is that the required data is unlikely to be available in many instances.

**Flux-Based Method:** Assuming that an initial starting condition can be identified at some pre-development time T (i.e. when the direction and magnitude of the exchange flux was known), one can then estimate subsequent fluxes directly from the stresses in the aquifer (e.g. a pump) using the appropriate analytical or numerical solutions then add them to the initial starting flux. The pre-development flux used should be a long-term average derived during non-flood event periods that represent base-flow conditions. Depending on the choice of T and how it relates to when the stresses had started (or will start), the full, or partial impacts of those stresses are superimposed on the initial starting flux to obtain the total exchange flux at any time (including extrapolation into the future). It is a pre-requisite in this method that pre-development initial conditions be identified and used as starting conditions, i.e. one must start from a ‘dynamic equilibrium’ steady-state state prior to development. Note that the pre-development flux will most likely be an unknown quantity that can implicitly accounted for in the calibration of the river model. This method does not require groundwater head data, which is mostly unavailable. However, there is a considerable effort in identifying all the stresses and collating the relevant data, which are derived from historical records.

**Mixed Head- and Flux-Based Method:** This option is a combination of the previously described methods. Referring back to the flux-based method, one can start at post-development conditions provided that an initial depth to groundwater can be identified and used to calculate an initial starting (transient) flux that accounts for the realisation of all the imposed stresses in the aquifer up to that particular time. Subsequently, the unrealised portion of the impacts from various stresses in the aquifer can then be superimposed on that flux to obtain the cumulative GW-SW exchange flux. Another case where one would need to adopt this method is when pressure heads are being imported from a groundwater model where a key process that leads to significant GW-SW exchanges fluxes might have been neglected such as evapotranspiration (ET) and/or flooding recharge, a very common practice in numerical modelling (e.g. using MODFLOW). In those cases, the flux time-series for every (neglected) stress can be calculated and subsequently superimposed on the fluxes imported from the numerical model.
Selecting the Appropriate Methodology

The process for selecting the appropriate methodology to estimate GW-SW exchange flux is mainly dictated by the type of connection between a river and the underlying aquifer:

1 Saturated Connection:
   - **Head-based method:** The most accurate and straightforward method for estimating the flux is based on knowledge of the head difference between the river stage and the watertable in the underlying aquifer at any time. However, in most cases such data may not be available. Alternatively, this data may be derived from a calibrated numerical groundwater model (i.e. MODFLOW) that accounts for all the relevant processes active in the field.
   
   - **Flux-based method:** For cases where the head data are not available, a flux-based approach may be adopted. In this approach, one should identify pre-development, steady-state conditions then progressively add the impacts of all stresses that had been acting to date; simulations can also extrapolate into future impacts. This method requires a comprehensive set of data that fully describes all the active stresses in the aquifer along with all the relevant parameters required to model their impact on the aquifer and nearby river.
   
   - **Mixed head- and flux-based method:** In some cases, one might opt to adopt a combination of the previous approaches. For example, if groundwater head data is available for a short period or there exists a data set with gaps, one can extract a representative head at some time to calculate a transient exchange flux then superimpose subsequent fluxes. The advantage with this method is that there is no need to start from pre-development conditions.

2 Unsaturated Connection: When unsaturated conditions develop beneath a river, some of the processes that contribute to the exchange flux between groundwater and surface water become either less relevant, or completely irrelevant. Therefore, implementing the flux-based approach based on assessing the impacts of individual stress becomes unreliable. For deep water tables where the maximum-loss condition has been realised, the flux becomes a function of the river stage irrespective of variations in groundwater levels. There is a transitional stage between a fully saturated connection and the maximum-loss conditions during which the relationship between the flux and the head gradient becomes non-linear (see Figure 7 of the Groundwater chapter of the Source Scientific Reference Guide; eWater, in press). Identifying this transitional stage is very difficult and given the high uncertainties associated with flux predictions, it is justifiable to neglect its effects. Rassam (2011) followed the same approach adopted in the River boundary of MODFLOW whereby the flux-head gradient relationship changes abruptly from linearity to independence.

The final selection of the methodology will also be largely impacted by data availability. Figure 3 is a decision-making flowchart that guides the user in making a decision on selecting the appropriate methodology for any situation. The relevant processes for each methodology type and the corresponding required parameters are listed in Table 1. The potential methods for estimating the exchange flux for every connection type are listed in Figure 4 and are discussed in more detail below.
Figure 3: flowchart for selecting the methodology for estimating GW-SW exchange fluxes in river system models (such as Source)
### Table 1: Data requirements to estimate GW-SW exchange fluxes in river system models

<table>
<thead>
<tr>
<th>Natural interaction</th>
<th>Pumping/Irrigation recharge</th>
<th>ET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base flow (non-event)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Within bank</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overbank</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturated connection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flux method</td>
<td>Predevelopment exchange flux</td>
<td></td>
</tr>
<tr>
<td></td>
<td>If estimating bank storage is required: Time series for river stage height in excess of base flow level; riverbed conductance**; aquifer hydraulic properties</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volume of water overbank; duration and area of inundation; area of wetlands its location relative to the river, and its volume; floodplain soil properties; depth of groundwater table; potential evaporation rate; aquifer hydraulic properties</td>
<td></td>
</tr>
<tr>
<td></td>
<td>If applicable: Pump/irrigation location as defined by the orthogonal distance to river and position relative to the Source nodes; aquifer hydraulic properties; pumping schedules; pumping rates; recharge details</td>
<td></td>
</tr>
<tr>
<td></td>
<td>If applicable: PET; land cover type; soil type; average depth to groundwater table; floodplain area</td>
<td></td>
</tr>
<tr>
<td>Mixed method</td>
<td>Transient head at some time $T_c$ during base-flow condition</td>
<td></td>
</tr>
<tr>
<td></td>
<td>As above; for times $&gt; T_c$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>As above; for times $&gt; T_c$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>If applicable: As above; for times $&gt; T_c$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>If applicable: As above; for times $&gt; T_c$</td>
<td></td>
</tr>
<tr>
<td>Head method</td>
<td>Time series for river stage height and groundwater head for entire simulation period; riverbed conductance**</td>
<td>N/A*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N/A*</td>
</tr>
<tr>
<td>Unsaturated connection</td>
<td>Non-linear</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Time series for river stage height and either time series for groundwater head for entire simulation period or average depth groundwater table</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Maximum loss</td>
<td>Time series for river stage height and depth groundwater table at which disconnection occurs</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N/A</td>
</tr>
</tbody>
</table>

* If head data is derived from groundwater model that has neglected this process, they need to be accounted for.

** As defined in Equation 2 in the Groundwater section of the Source Scientific Reference Guide; eWater, in press) (calculating riverbed conductance requires: $K$, the hydraulic conductivity of the riverbed sediments; $L$, the length of the river link; $W$, the width of the river link; and $M$, the thickness of the riverbed sediments).
Figure 4: Flowchart for selecting the methodology for estimating GW-SW exchange fluxes based on connection type

1. Head-based means to calculate flux based on head gradient and conductance; Flux-based means to calculate flux directly from individual stresses (such as stream depletion ET etc.) and then sum them up.
2. No flux calculation for individual stresses is required as their impact is already built into the known head.
3. A flux time series for every stress is calculated (eg stream depletion fluxes from URE, ET flux, overbank flux, etc) then summed up to obtain a time series of cumulative impact; choice of starting time is critical.
4. May be included in the calibration process.
5. Can use a time-variable head (if time data is available) but an average value is accurate enough as the head effects diminish for unsaturated connection.
6. No flux calculations for individual stresses are warranted as processes become increasingly irrelevant with deeper groundwater tables (eg no bank storage), no return from from irrigation or overbank flooding, no ET. Furthermore, conventional analytical solutions break down under unsaturated conditions (eg boundary conditions for stream depletion solutions become fundamentally different).
Calibrate model

All the guidance on model calibration in the generic guidelines is relevant to implementing GW-SW interaction models in Source. However there are additional calibration considerations when using groundwater models with river models.

As described in Section 1.1, a key challenge in modelling GW-SW interactions is the significant time-scale differences between surface water and groundwater processes. River models are typically calibrated to achieve mass balance within calibration reaches over relatively short time periods. When the models are run for extended periods the relationships derived during calibration are assumed to hold for the full modelling period. However, the calibration period may be a period of changing groundwater extraction and a period of changing impact of this extraction on the river system (e.g. Figure 5). It is therefore necessary to determine the equilibrium conditions of surface and groundwater systems considering their interactions and the considerable lag times involved in reaching equilibrium.

![Figure 5: Timeline of groundwater use and resultant impact on a river (CSIRO, 2007)](image)

Existing river systems and groundwater models

The first major attempt in Australia of incorporating GW-SW interactions in rivers systems modelling was the MDBSY project (CSIRO, 2008). In this project it was felt that by running the groundwater models until a ‘dynamic equilibrium’ was reached, a reasonable estimate of the ultimate impact on the river of current and future groundwater use would be obtained. The ‘dynamic equilibrium’ approach used in the MDBSY project involved running groundwater models for an initial 111 years of climatic data (the same modelling period as the river models) to allow the groundwater models to evolve to ‘dynamic equilibrium’ (i.e. a ‘warm-up’ period), followed by another 111 years to estimate exchange fluxes to/from the surface water during varying climate and groundwater extraction. Then, the groundwater fluxes for a given state of groundwater extraction were compared to the fluxes during the calibration period of the river model, allowing the river fluxes in the river models to be modified accordingly. At the end of the MDBSY project a review of the ‘dynamic equilibrium’ approach and other issues was carried out (Rassam et al., 2008) which included the following recommendations of relevance to this guidance:

1. Ensure that ‘dynamic equilibrium’ is reached. This is achieved as follows:
a. Calibrate groundwater models for steady-state conditions, preferably from a without-development state. This ensures that the simulation is sufficiently stable in order to be able to be run over periods of 100 years in line with river models.

b. Ensure that groundwater extractions are sustainable so that 'drying out' of aquifers does not occur.

c. Simulate for a long enough time to ensure that the impacts of the imposed stresses are fully realised.

2 Groundwater models should have sufficiently large areas to ensure that the imposed boundary conditions are distant enough so that they do not lead to artificial inflows that may occur due to prolonged run times.

3 Use consistent calibration periods for river and groundwater models where the impacts of groundwater development are accounted for in river model calibration and river management rules are accounted for in groundwater model calibration.

4 Need for greater automation for changing input and output files in both groundwater and surface water models. This includes dealing with floods in a predictive sense, changing flows into stage heights and interpolation between gauging stations and including changes in fluxes into loss and inflows to river models.

5 Need to ensure groundwater extraction data includes the distance from the river and the aquifer being used.

6 Need to better handle areas with wide floodplains and shallow groundwater levels where the effects of evapotranspiration and flood recharge are taken into consideration.

Rassam et al. (2008) also recommended that alternative approaches to the dynamic equilibrium approach should be considered in order to avoid some of the associated problems. They suggested that running river models for 20 to 30 years stochastically and then statistically selecting representative head time series and importing them into groundwater models may overcome the problems associated with running the groundwater models for prolonged durations (over 100 years). They also suggested that once the exchange fluxes are imported back to river models, they should be re-calibrated, with storages modified accordingly. It should be note that while this approach is conceptually attractive, it has not yet been tested, and requires a significant shift in the paradigm for calibrating river models. It is therefore an area of future research outside the scope of eWater.

New generation Source model

Rassam (2011) recently conceptualised the calibration of Source in the presence of groundwater processes. As the model includes both surface and groundwater processes, its calibration would entail concepts from both the surface water and groundwater systems. The calibration would still be against observed flow data at a downstream gauge with two additional groundwater parameters, namely, aquifer diffusivity and riverbed conductance. However, one can independently calibrate the groundwater parameters and keep them constant (or implement bounds to their variability) during calibration of the river model to control the non-uniqueness problem. This can be done outside of Source using analytical solutions for the application of a flood wave response to estimate aquifer diffusivity and river conductance using the groundwater levels of a floodplain observation well.
An important issue that needs to be highlighted here is the timing of the delayed impacts of the groundwater processes and how they relate to the calibration period of the river system model. Referring to Figure 6, one can assume a pre-development era when the coupled surface-groundwater system was at equilibrium, thus resulting in a steady-state exchange flux, \( Q_{pd} \). Groundwater extractions would upset this state of equilibrium resulting in a new exchange flux that is time-variant. With a high level of groundwater development, one would expect this to be the status quo almost everywhere. Therefore, the calibration period of a river model would most likely coincide with a groundwater system that is at a transient state where the flux, during part or the entire calibration period, is time-variant. The traditional calibration of river models such as IQQM (Simons et al., 1996) implicitly accounts for this time-variant GW-SW exchange flux. However, when the model is operated in a forecasting mode, it would disregard the effect of the unrealised impacts of existing developments as well as the impacts of future developments.

Source overcomes this problem as it explicitly accounts for the interaction between surface and groundwater via the GW-SW Link Module. To achieve a realistic calibration that results in a model with a strong forecasting capability, one must historically track all the changes in aquifer stresses and model their impacts prior to, and during the calibration period of the river model (\( t_0 - t_2 \) in Figure 6), and continue to account for their unrealised impacts during a subsequent forecasting simulation (\( t_2 \) to \( t_3 \) in Figure 6). Note that the pre-development flux will most likely be an unknown quantity that is implicitly accounted for in the calibration of the river model (which maintains mass balance).

\[
\begin{align*}
Q_{C}(T_{1,2}) &= Q_{pd} + Q(T,C,D) \\
Q_{F}(T_{2,3}) &= Q_{c} + Q(T,C,D)
\end{align*}
\]

Figure 6: Schematic showing relation of GW-SW exchange fluxes to calibration and forecasting periods for river model (Rassam, 2011)

**Sensitivity/uncertainty analysis**

The sensitivity analysis discussion in the option modelling section of the generic guidelines is relevant to implementing GW-SW interaction models in Source. Sensitivity analysis is a routine procedure in groundwater and river modelling that enables uncertainties in model output to be systematically apportioned to different sources of uncertainty in the model inputs.
(particularly parameter values). It is usually undertaken as an adjunct to model calibration and validation.

However, the uncertainty analysis discussion in the option modelling section of the generic guidelines is only partly relevant to implementing GW-SW interaction models in Source. As discussed in Section 0, uncertainty analysis techniques for groundwater modelling have not been widely adopted in Australia, let alone for GW-SW interaction modelling specifically. This is clearly an area of future research.

2.4 Identify preferred option

The general philosophy in the section of the generic guidelines on identifying the preferred option is relevant to implementing GW-SW interaction models in Source.

Techniques for selecting the “best” option

The general philosophy of the guidance in the section on techniques for selecting the best option in the generic guidelines is relevant to implementing GW-SW interaction models in Source; however implementation of the recommended methods is difficult given the current immaturity of GW-SW interaction modelling. The concept of developing a Pareto front of a set optimal solutions that satisfy multiple objectives (see Figure 5 in the generic guidelines) has been used in the groundwater domain, particularly for remediation of contaminated groundwater (e.g. Mantoglou and Kourakos, 2007; Singh and Chakrabarty, 2010). While it has been used in at least one overseas study for GW-SW interactions (Schoups et al., 2005) it is certainly not a routine approach. Multiple criteria analysis (MCA) has widespread and growing application in the field of water management (Hajkowicz and Collins, 2007), and is starting to be used for groundwater management (e.g. Almasri and Kaluarachchi, 2005). However, to date no studies of GW-SW interaction that utilise MCA are known.

Performance Criteria

Performance criteria for use in the context of a decision making process should be decided in consultation with stakeholders at the start of the project, and preferably during the problem definition phase of the project, as discussed in Section 0.

Finding the “best” option

The general philosophy of the guidance in the section on finding the best option in the generic guidelines is relevant to implementing GW-SW interaction models in Source, keeping in mind the current limited use of optimisation and MCA in GW-SW interaction modelling. It is important to note, however, that the process proposed for selecting the “best option” (Blackmore et al., 2009) has never been tested in the groundwater domain, let alone in GW-SW interaction specifically.

Report/communicate comparison of options

The guidance in the section on report/communicate comparison of options in the generic guidelines is relevant to implementing GW-SW interaction models in Source.
Chapter 3 in the generic guidelines is relevant to the implementation of GW-SW interactions in river system models. In addition, Rassam and Werner (2008) provide a comprehensive review of GW-SW interaction modelling approaches and their suitability for Australian conditions. They identify a number of important considerations in selecting a modelling approach:

1. The spatial scale at which a model is applied dictates its level of complexity and hence what processes are, and are not accounted for. Large-scale models usually adopt a lumped approach that requires less parameterisation whereas smaller scale physically based models can explicitly account for more processes. Identifying the dimensionality of any problem is of vital importance as model complexity varies in an exponential manner with model dimensionality (a 10-element 1-D model, has 100 elements in a 2D model, and 1000 elements in a 3D model).

2. Data requirements are closely related to model complexity and the spatial scale at which the model operates. Lumped models require less data whereas process-based models require much more data. In many cases, model choice is restricted by data availability. At a whole-of-river scale, readily available data can support low fidelity modelling whereas intensive measurements at a sub-reach scale may be needed to support high fidelity modelling.

3. When choosing modelling tools for GW-SW interaction, it is important to strike the right balance between SW and GW processes. That is, we need to clearly define the problem and hence identify whether or not any emphasis should be placed on GW or SW processes; this would clearly significantly impact model choice.

4. The issue of temporal scales becomes critical when modelling GW-SW interaction as SW processes are quick whereas GW processes are much more attenuated. Large time lumping in evaluating a particular process may mask other processes that may occur during short periods as a result of the averaging effect of larger time interval data. Large disparities in time steps between SW and GW may lead to numerical instabilities.
4 Further reading

A small number of groundwater modelling guidelines already exist; the most widely cited internationally are the Murray-Darling Basin Commission’s Groundwater Flow Modelling Guideline (Middlemis et al., 2000) and the United States Geological Survey’s Guidelines for Evaluating Ground-Water Flow Models (Reilly and Harbaugh, 2004). GW-SW interactions are briefly discussed in both of the guidelines but are not at major focus; they are approached from a purely groundwater perspective whereby the streams are just considered as groundwater model boundary conditions. It is also important to note that the National Water Commission has recently embarked on the development of National Groundwater Modelling Guidelines that build upon those of Middlemis et al. (2000) but these are not yet complete. It is planned they these will include GW-SW interactions, although it is likely that they will be from a groundwater perspective rather than a river system modelling perspective. Another source of reference material is the book on groundwater model calibration by Hill and Tiedeman (2007) which develops a set of guidelines for effective groundwater modelling, although none is specific to GW-SW interactions. The guidelines on groundwater model calibration and uncertainty analysis are very useful (see Doherty et al. (2010); Doherty and Hunt (2010); and Doherty et al. (2011)).
5 Glossary

The Glossary in Chapter 5 of the generic guidelines is relevant to the implementation of GW-SW interactions in river system models. In addition, some key terms related to GW-SW interaction are presented in the table below.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Aquifer</td>
<td>Saturated permeable soil or geologic strata that can transmit significant quantities of groundwater under a hydraulic gradient.</td>
</tr>
<tr>
<td>Discharge</td>
<td>Loss of water from an aquifer (i) to the atmosphere by evaporation, springs and/or transpiration, or (ii) to a surface water body (in the case of rivers it is generally referred to as base flow) or the ocean, or (iii) by extraction.</td>
</tr>
<tr>
<td>Gaining</td>
<td>Water flow from a groundwater system into a river.</td>
</tr>
<tr>
<td>Groundwater</td>
<td>Sub-surface water in soils and geologic strata that have all of their pore space filled with water (i.e. are saturated).</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>A measure of soil or rock’s ability to transmit water when submitted to a hydraulic gradient.</td>
</tr>
<tr>
<td>Hydraulic gradient</td>
<td>Change in hydraulic head in an aquifer with either horizontal or vertical distance, in the direction of groundwater flow.</td>
</tr>
<tr>
<td>Losing</td>
<td>Water flow from a river into a groundwater system.</td>
</tr>
<tr>
<td>Recharge</td>
<td>Addition of water to an aquifer, most commonly through infiltration of a portion of rainfall, surface water or irrigation water that moves down beyond the plant root zone to an aquifer.</td>
</tr>
<tr>
<td>Riverbed conductance</td>
<td>Hydraulic conductivity of the riverbed material multiplied by the width of the river multiplied by the length of the link divided by the thickness of the riverbed.</td>
</tr>
<tr>
<td>Saturated connection</td>
<td>One where there is no unsaturated zone between the river and the water table.</td>
</tr>
<tr>
<td>Unsaturated connection</td>
<td>One where there is an unsaturated zone between the river and the water table.</td>
</tr>
<tr>
<td>Unsaturated connection – maximum loss</td>
<td>One where there is an unsaturated zone between the river and the water table and it is sufficiently thick that the maximum loss rate of river water to the water table has been achieved.</td>
</tr>
<tr>
<td>Unsaturated zone</td>
<td>Zone between land surface and the water table within which the moisture content is less than saturation (except in the capillary fringe).</td>
</tr>
<tr>
<td>Water table</td>
<td>Level of groundwater in an unconfined aquifer. The soil pores and geologic strata below the water table are saturated with water.</td>
</tr>
</tbody>
</table>
6 References


Guidelines for groundwater-surface water interactions modelling


