ACCURATE SIMULATION METHODS FOR BRAIDED RIVERS IN NUMERICAL GROUNDWATER MODELS

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Abstract

The focus of this paper is the system bias present in groundwater models using rectangular cross-sections to represent rivers, and especially wide or braided rivers. The accurate description of surface water-groundwater interaction is of key importance today as more and more regions manage surface and ground waters conjunctively. This is especially true in basins where the most significant groundwater recharge source is loss from surface water bodies. The bias is due to the inaccuracies of the relationship between depth and flow as well as in the model for bed conductance which should be a function of river stage. This is demonstrated via analytical examples as well as site specific models in New Zealand. The site specific models have been developed using the traditional Stream Package (STR) in MODLFOW, as well as the new Stream Flow Routing Package (SFR1). These are compared to a MIKE SHE model using MIKE 11 for the stream flow calculations. The STR, SFR1 and MIKE 11 all use Mannings equation for flow routing along the river. However, SFR1 and MIKE 11 determine bed conductance as a function of stage, whereas STR does not. The case study allows the direct comparison of the performance of the two different representations for river flow. System dynamics are more accurately achieved as a result of the more accurate relationship between flow and stage; which has direct influence on the gradient between the river and the groundwater system. Furthermore, MIKE 11 also allows the river time step to be disconnected from the groundwater time step, allowing for more accurate representation of flow events that are shorter than a groundwater time step. There are three key results from this work: (1) groundwater surface water interaction is more accurately simulated using realistic cross-sections compared to using rectangular cross-sections, (2) short term flow events have impact the groundwater dynamics and (3) the dynamics of simulated time series at wells and springs along rivers are much closer to what is observed.

1. BACKGROUND

There is an increasing focus on the conjunctive management of surface water and groundwater. One example of this is the European Unions Water Framework Directive [EU, 2000]. Aquifers in semiarid areas are recharged by mountain and foothill streams and rivers and the optimal management of such aquifers, and rivers, requires a description of the exchange of water between surface water bodies and groundwater [McPhee and Yeh, 2004]. In New Zealand up to 84% of the recharge to some significant aquifers comes from losses from rivers [Rosen et al.,2001]. Given the importance of the interaction between groundwater and surface water, it is vital that this is represented accurately in groundwater models.

We will demonstrate with analytical models and numerical modeling that the classic approach utilizing rectangular cross-sections for rivers to modeling surface water-groundwater interaction introduces errors for many hydrologic systems. The reasoning behind this is 2 fold: First the classic rectangular cross section has a constant conductance term, while in reality conductance varies as a function of the wetted perimeter of the surface water feature. Secondly, The stage - flow relationship for a rectangular cross section is not valid for braided river systems; as well as other rivers with shallow sloping channel geometries.

In our theoretical development we will show some simple examples of the types of error that can be generated due to the assumption of a rectangular cross-section for a braided river system. As a surrogate for the braided river cross-section we will use a shallow V-shaped channel.

We also present a case study based on a field example. The example is for the Wairau Aquifer in the North of the South Island of New Zealand. Modeling attempts for the aquifer began in 1988; and it was recognized early on that it is essential that the mechanism linking river losses to the aquifer was adequately defined to ensure the model reflects reality. There were a number of attempts to model the system using various generations of the river and stream packages within the MODFLOW modeling system. It was first with the introduction of models that utilize measured cross-sections that the surface water-groundwater exchange could accurately be represented. We apply two systems approaches that utilize realistic river cross-sections in a groundwater model: MODFLOW with the SFR [Prudic et al., 2004] and MIKE SHE [DHI, 2005].

2. THEORY

The conceptual problem for a rectangular versus irregular channel is illustrated with Figure 1 using a simple V-channel. In the case of using a rectangular cross-section, the contact area with the groundwater is a constant width (w), while for an irregular cross-section, the contact area is a function of the length of the wetted surface ($w(Q_R)$). Furthermore, the relation between stage (s) and flow in the river (Q_R) is substantially different for the two different model channel geometries.

The result of this is that the conductance for the rectangular cross-section is:

$$C_{BED} = K_{BED}\, w\, L\, t \tag{1}$$

While for a variable cross-section it is:

$$C_{BED} = K_{BED}\, w'(Q)\, L\, t \tag{2}$$

where C_{BED} is the bed conductance, K_{BED} is the bed hydraulic conductivity, w is the wetted perimeter of the channel, t is the bed thickness, and L is the length of the channel in the cell of interest.

Figure 2 shows the difference in exchange between surface water and groundwater as a function of depth, where conductance is a function of the wetted perimeter for the V-shaped cross-section and constant for the rectangular cross-section. Note that the

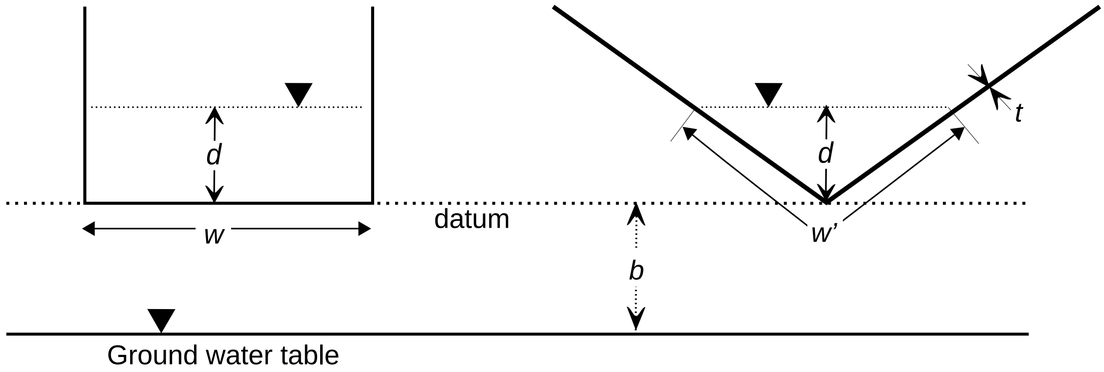


FIGURE 1. Schematic of the groundwater-surface water exchange problem

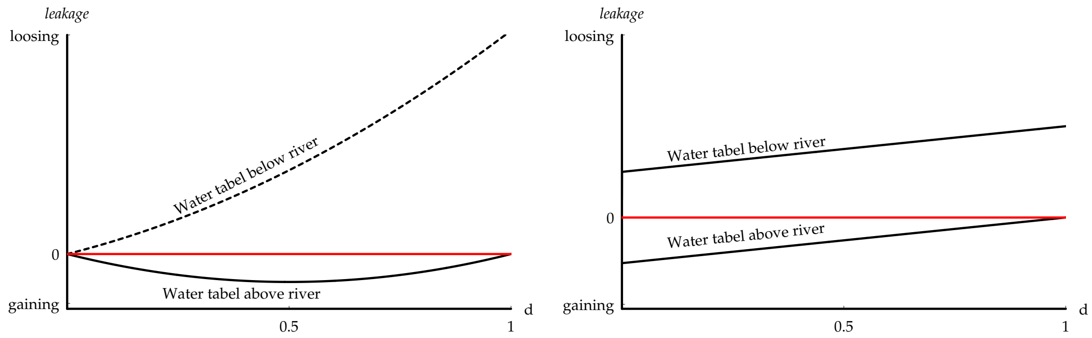


FIGURE 2. Loss and gain to a river, left rectangular (Equation 2) and right a V-shaped (Equation 2) cross-section.

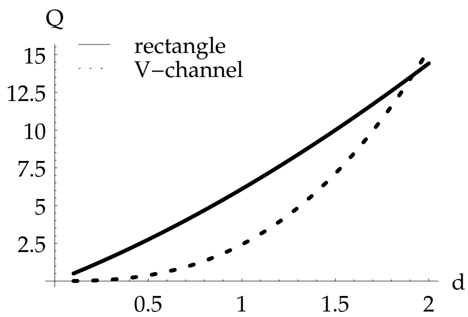


FIGURE 3. Flow along a river as a function of depth for rectangular cross-section and a V-shaped cross-section

response presented in Figure 2 is for a relatively simple example, V channel, and given more irregular channels, a more pronounced non-linear effect will be observed.

The non-linearity of the response is also a function of the flow routing. In a rectangular cross-section, flow will vary linearly as a function of depth. However, this is not true in the case of irregular cross-sections. Figure 3 shows a simple case where flow is plotted as a function of depth for rectangular and V-shaped cross-sections.

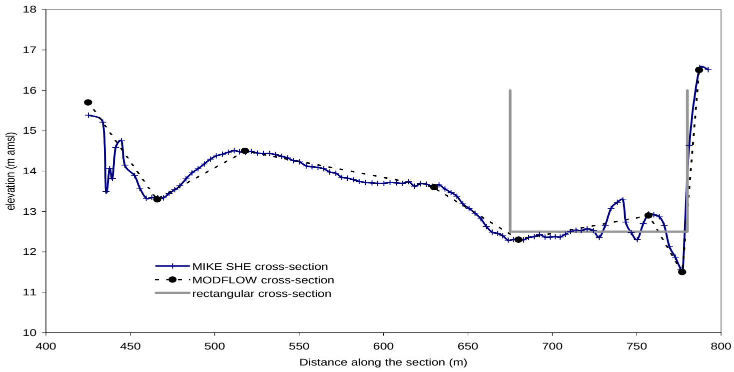


FIGURE 4. Comparison of a measured channel cross-section as implemented in MIKE SHE and an 8-point discretisation for SFR (for comparison, a rectangular cross-section is also shown).

The overall effect of introducing more accurate flow routing mechanisms directly into the groundwater system is that one moves from responses being linear, to becoming non-linear. This is an import factor when analyzing system response and developing management plans.

3. CASE STUDY

The Wairau Aquifer is a key source of potable water and irrigation water for an economically significant area in the North East of the South Island of New Zealand. By the 1990s, the allocation limit of 4 m3/s specified in the Proposed Wairau Awatere Resource Management Plan had been exceeded via the resource consent process. Depletion of the Wairau River and other culturally important surface water bodies, mainly springs, by excessive groundwater pumping is the key concern.

A series of model development projects were initiated to aide management starting with a steady-state model ([PDP, 2001]) and progressing to transient models ([Aqualinc, 2003]) using the stream (STR) package [Prudic, 1989]. The STR package can simulate flow routing, but only in rectangular channels. The model built using the STR package still has the problem of channel losses not reflecting observed surface water groundwater exchange. However, it was soon determined that it was difficult to accurately simulate groundwater-surface water interaction along the Wairau River at both high and low flows. Basically, the model could not accurately simulate the stage (s) versus flow (Q_R) relationship, as only a rectangular geometry is available.

These attempts led naturally to the work presented here; as a decision was taken to replace the rectangular cross-sectional model in the STR model with a model that could use more representative cross-sections. Two possibilities presented themselves: Firstly, the USGS MODFLOW model [Harbaugh et al., 2000] using the SFR package [Prudic et al., 2004]. This package allows for using 8-point cross-sections for rivers, where the wetted perimeter varies with flow, and Mannings equation is used for flow routing. At the same time, MIKE SHE developed by DHI Water and Environment utilizes a hydrodynamic solution for river flow. This approach has the advantage that the surface water flow is computationally disconnected from the groundwater simulation. Therefore, the

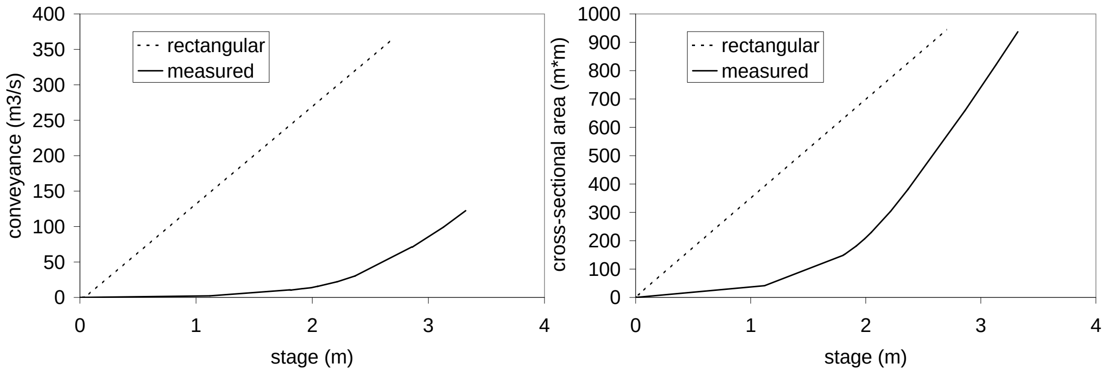


FIGURE 5. A comparison of cross-sectional area and conveyance between a rectangular and measured cross-section as a function of stage.

groundwater and surface water can each have their own individual time stepping, that results a more stabile and accurate surface water simulation; while avoiding very small time steps for the groundwater part of the simulation.

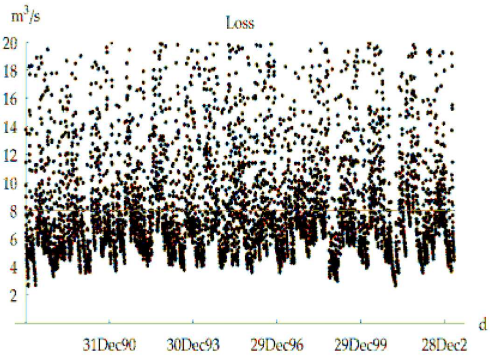
An example of the implementation of the measured cross-sections is shown in Figure 4 for both the MIKE SHE model as well as the SFR MODFLOW model. For other rivers in the model where a measured cross-section was not available, a rectangular or a V-shaped cross-section was used.

As an example of the $s - Q_F$ differences for a rectangular versus a measured cross-section; cross-sectional area and conveyance are plotted up for 2 cross-sections of the Wairau River as a function of stage (Figure 5). Figure 5 shows the significant difference between the two approaches to represent rivers in groundwater models.

Model calibration uses head data and river losses derived from gauging data, while verification uses flow data for the Wairau River and Spring Creek. Model calibration was carried out partially manually and partially using auto-calibration. MODFLOW2000s implementation of measured cross-sections [Prudic et al., 2004], can only use MODFLOW2000s built in auto-calibration routines [Hill et al., 2000] if changes to the source code are carried out. However, parameter estimation could be carried out using other techniques (e.g. shuffled complex evolution [Vrugt, et al., 2003]). The model calibration ended with a standard error of 0.05.

The parameterization of the bed conductance applied to the river bed is also simplified compared to what was necessary in the model with the rectangular cross-sections. In the earlier versions of the model, relatively complicated conductance parameterization was required in order to maintain realistic river leakage rates at all flows. That may have been one of the reasons that the exchange of water was so different compared to what is observed as well as simulated with the SFR and MIKE SHE models.

The models implementing measured cross-sections have a very simple parameterization. In part, this may be due to the fact that stream bed conductance, when using a rectangular cross-section, must implicitly contain information about the shape of the channel, while this information is explicit when more realistic channel geometry is applied. The bed conductance in the models with the measured cross-sections has two parameter zones: a downstream and an upstream. The downstream zone coincides with where the river lies



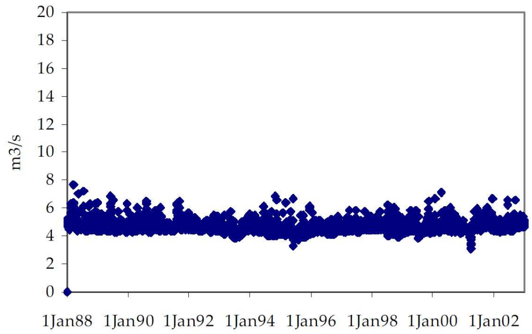


FIGURE 6. Simulate river losses from models implementing measured (left) versus rectangular (right) cross-sections.

in finer sediments, while the upstream zone coincides with where the river lies in coarser sediments.

The implementation results in a more variable stream leakage from the Wairau River (Figure 6), which fits observations. This is probably due to the large change in bed conductance (C_{BED}), that occurs changing from the rectangular cross-sections to measured cross-sections. The Wairau river is broad with a relatively flat cross-section so that small changes in stage result in large changes in C_{BED}, while there is only a small change in head gradient (4). In the case where there is a rectangular river channel, more or less the opposite occurs, although with a very different response function.

Figure 7 shows the errors in surface water flows for the two different approaches. The error is slightly lower with measured cross-sections. However, what is more interesting is that the tail of the distribution of errors is moved from over estimating flow to under estimating flow. This is what one should see in a model that does not include quick-flow components of the hydrograph. Note that if the model overestimates surface water flow, then insufficient water is reaching the groundwater system.

The groundwater model with measured cross-sections, on average, underestimates surface water flow by 8%. This is more in line with what is expected, despite the fact that the rectangular cross-section model lost too little water to the groundwater system.

Part of the result is that the response seen in the aquifer discharge points is quite different between the two simulation methods (Figure 8). This is despite similar values for hydraulic conductivity, storage coefficients and drain conductances.

There is also important changes in the response within the aquifer itself, as illustrated by the hydrograph from a monitoring well (Figure 9). The simulated response with the measured cross-sections is more dynamic and closer to what is observed. There is still a bias in the model, with head near the rivers being higher than what is observed. The general conclusion is that the head bias near the river must have a source other than groundwater-surface water interaction (i.e. the geological description needs to be improved).

The bed conductances that are implemented in the model with measured cross-sections are very different from what was used with STR. Bed hydraulic conductivities (K_{BED}) range between around 1 m/d to 100 m/d with the measured cross-section models, while

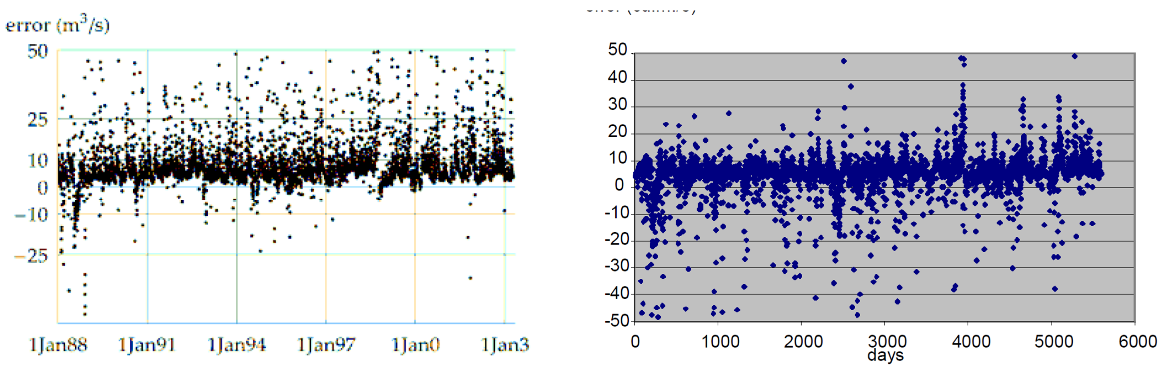


FIGURE 7. Error (observed minus simulated) river flows in the Wairau River (left measured cross-sections, right - rectangular)

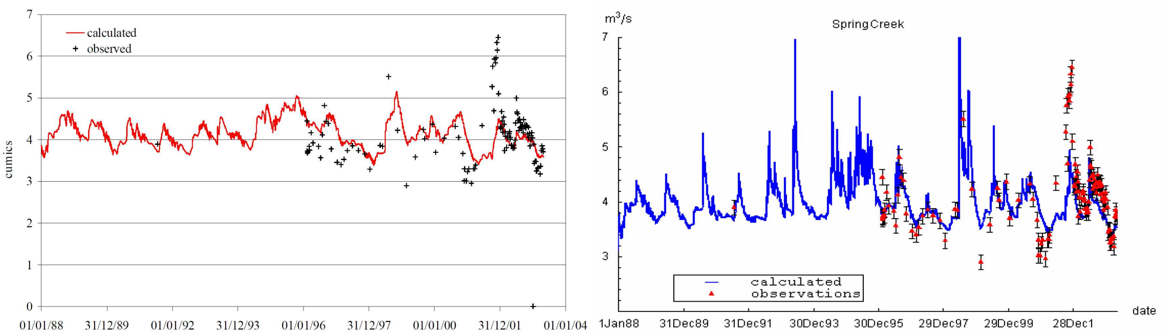


FIGURE 8. Spring discharge using measured (left) and rectangular cross-sections for the Wairau river

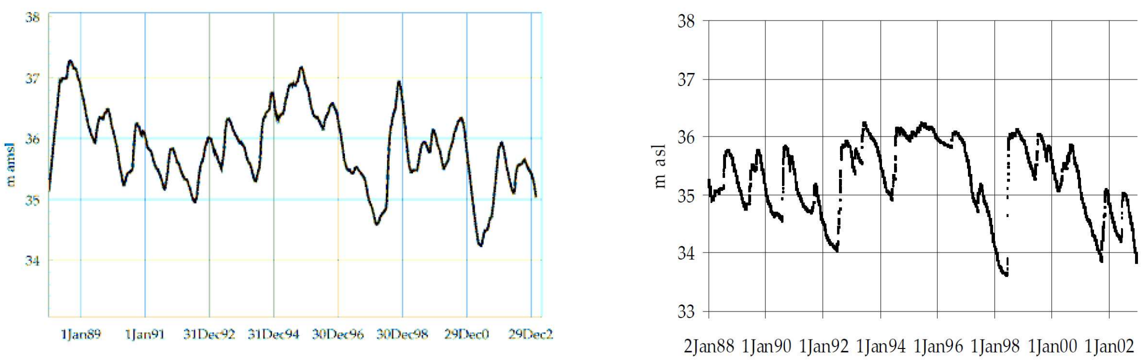


FIGURE 9. Simulated head from models using a measured (left) versus rectangular (right) cross-sections.

K_{BED} values two to three orders of magnitude lower were required with the STR-based model.

Spring flow is an indicia of aquifer health, and so improving the predictions for discharges from the springs is important in managing groundwater pumping. The model suggested that the volume required for full development of the Wairau Plain to enable pasture or crop irrigation was unlikely to be sustainable.

4. Conclusions

We show the need for accurate descriptions of surface water feature geometries, with in groundwater models, for accurately determination of the exchange between surface water and groundwater. We built our arguments on the results from analytical and numerical simulations. There are three key results from the implementation of measured cross-sections for rivers within a groundwater model. The first is that the implementation of measured cross-sections allows for correct stage-river flow relationships which in turn results in more accurate gradients between the surface and ground-water components in the system. Secondly, the dynamics of simulated time series at wells and springs along a braided river are much improved compared to what can be developed with rectangular cross-section models. A third observation is that K_{BED} values are more realistic, as the need to implicitly contain information about the $s - Q_F$ relationship within bed conductance is removed; C_{BED} is a function of Q_R.

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