Modeling Groundwater Interactions using Analytic Element Methods and LiDAR

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Abstract

A distributed-parameter water budget for the Boise Valley, Idaho, yielded unexpected results along a specific reach of the Boise River during the non-irrigation season. A groundwater model was developed using a combination of analytic element methods (AEM) and LiDAR elevation data. The model objectives were: to perform a more detailed analysis of the interactions between this reach and the underlying aquifer, to determine if the water budget calculations were plausible, and to better understand the role of canals and drains in the river-aquifer interaction. The AEM approach represents hydrologic features individually and therefore is capable of model results with high spatial resolution. To achieve this high level of resolution, however, AEM models generally require intensive input data development. The availability of LiDAR for the study area made it possible to more efficiently develop a geospatial database of hydrologic features and elevation values for model input.

Introduction

Groundwater models are useful tools that allow for better understanding of groundwater movement, contaminant transport and the interactions between ground and surface water. With the growing interest in understanding groundwater and its behavior, groundwater modelers are often limited in the amount of time they have to develop reliable models

Models can be very time consuming to populate with diverse and dense data values and therefore, it can take a long time to get results from the model. Increased efficiencies in populating groundwater models and obtaining model results can be realized by integrating geospatial data and GIS tools. Consequently, data intensive groundwater models are becoming viable tools.

The analytic element method (AEM) is one modeling method that is currently being integrated with GIS data. The AEM method can be used to study groundwater movement, contaminant transport and the interactions between surface and groundwater with respect to features such as rivers, canals, and wells. In the past, defining the elements was a tedious task requiring lots of data and patience.

Since the elevations of surface features such as rivers, drains and canals, are often required data in an AEM model, it is critical to have a reliable source of elevation data for these features. Light detection and ranging (LiDAR) data can provide elevation data accurate to within 3.2 cm (RMSE). Within a GIS, this data can be analyzed, processed and exported to the AEM model, thus enabling the most accurate modeling results possible.

The purpose of this paper is to present the results of an AEM modeling study in which LiDAR was the primary source of elevation data used in the model.

Motivation for Study

Groundwater modelers develop water budgets to determine the location and quantity of water entering or leaving an aquifer. For example, to answer certain surface and groundwater interaction questions, it is often necessary to quantify how much water is entering and leaving the aquifer via a particular river. In the case of this study, a distributed-parameter[i],GIS based, water budget of the Boise Valley (Figure 1) indicated that a reach of the Boise River (between Glenwood Bridge and Middleton) was gaining water[ii] during the irrigation season and losing water during the non-irrigation season; in other words, water was entering the shallow underlying aquifer during the irrigation season and leaving the aquifer during the non-irrigation season (USBR and IDWR, 2006).

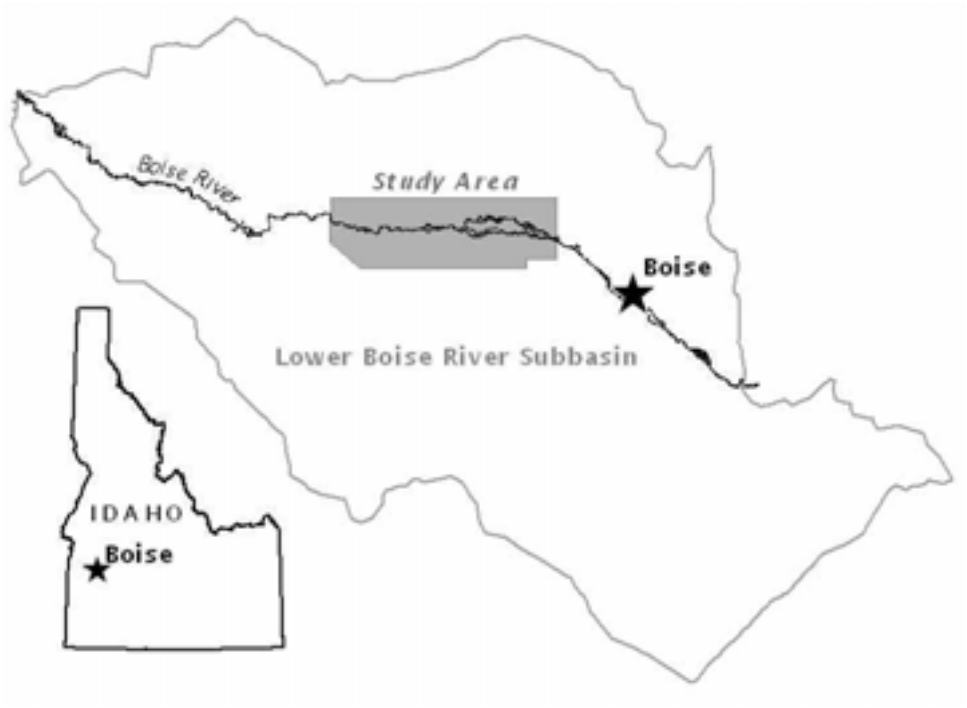

Figure 1: Eagle Island AEM model study are within the Boise Valley.

Based on general knowledge of the region, it was expected that the aquifer would be gaining during the irrigation season, however, it was completely unexpected that the aquifer would be losing during the non-irrigation season. A groundwater model of the area was developed to determine whether the water budget results were plausible.

It is possible to investigate this problem using a finite difference model such as MODFLOW. However, a finite difference model will produce a solution that is limited by the resolution of the finite difference grid size. On the other hand, an AEM model such as GFLOW gives an exact solution at an exact place.

Modeling Objectives

The objective of groundwater modeling was to determine the nature of interactions between the Boise River in the Glenwood Bridge to Middleton reach, and the shallow underlying aquifer. Specifically, the following questions were addressed:

1. Is the river-aquifer interaction that occurs during the irrigation season different from the interaction during the non-irrigation season?

2. What quantity of water is involved in river-aquifer interactions during the irrigation season and during the non-irrigation season?

3. What is the role of the canals and drains in determining river-aquifer interactions?

4. Are the Boise Valley water budget estimates of irrigation season and non-irrigation season river reach gain and loss plausible?

Analytic Element Methods and GFLOW

Analytic elements are solutions to the governing differential equation for steady-state[iii] groundwater flow, which is a combination of Darcy's Law and conservation of mass.

Darcy's Law

Darcy's Law, developed by Henry Darcy in the 1850's, proportionally relates the flow, Q [l^3/t], through a porous media (e.g. sand) to the change in hydraulic head, $\Delta h = (h_1 - h_2)$ [l], in the media. Figure 2 shows the apparatus Darcy used to develop the theory along with the Darcy equation.

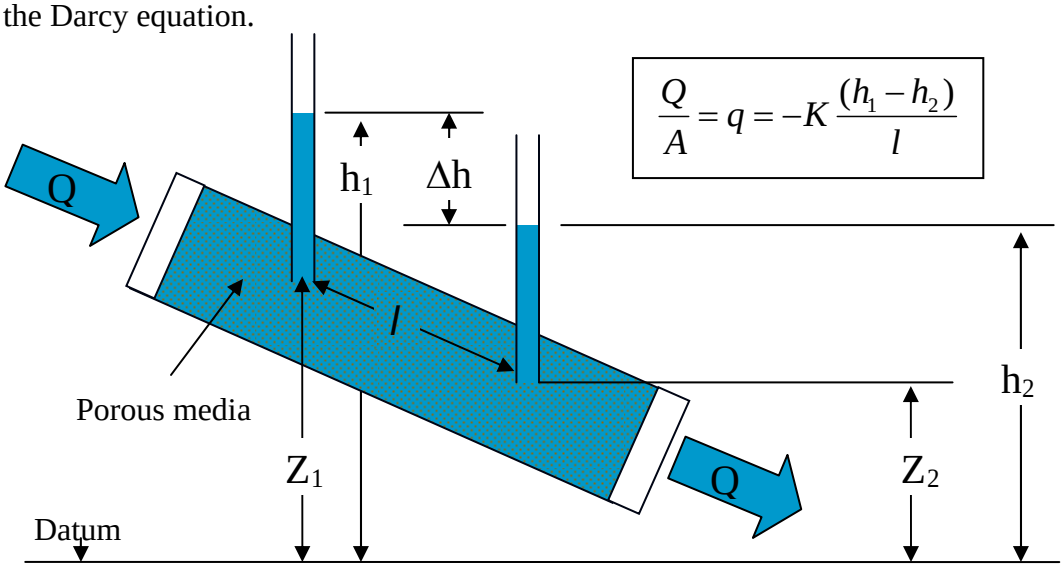

Figure 2: Darcy apparatus (Domenico and Schwartz, 1990) and Darcy equation that relates hydraulic head to flow though the porous media.

The proportionality constant that relates the flow to the change in head is the hydraulic conductivity, K [l/t], of the media, which is dependant on the type of media. For example, sands have a higher hydraulic conductivity than clays (Haitjema, 1995).

Conservation of Mass

Conservation of mass simply states that within a given volume, the inflow, Q_i, minus the outflow, Q_o, must equal the change in storage (Haitjema, 1995). Figure 3 illustrates this principle.

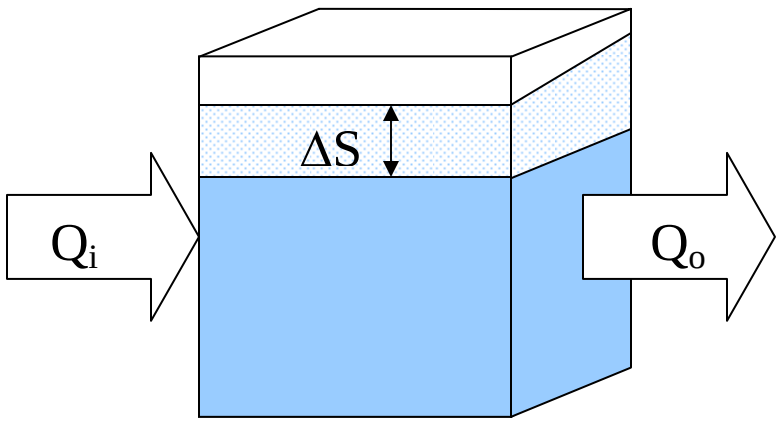

Figure 3: The change in storage, ΔS, within a given volume (the cube) is equal to inflow, Q_i, minus the outflow, Q_o, from the volume.

Equation of Groundwater flow

Darcy's Law and conservation of mass are combined to form the two-dimensional steady-state governing equation for groundwater flow:

$$\frac{\partial}{\partial x}\left[-k\frac{\partial \phi}{\partial x}\right]+\frac{\partial}{\partial y}\left[-k\frac{\partial \phi}{\partial y}\right]=0$$

This equation simply describes the movement of groundwater in the x and y directions based on the change in head, ϕ, and the hydraulic conductivity, k, in each direction (Haitjema, 1995).

Analytic Elements

Individual analytic element solutions can be used to represent aquifer interactions with

hydrologic features such as wells, rivers, drains, reservoirs, and aquifer heterogeneities. Analytic element features can be either head-specified or flow-specified (or a combination of both). The AEM model calculates a solution for each feature using the governing equation for groundwater flow described above.

Individual analytic element solutions can be superimposed on one another in order to develop comprehensive solutions for problems involving a large number of hydrologic features. Because they represent each hydrologic feature individually, analytic element models (AEM) are capable of very high spatial resolution in terms of model results. Superposition is a widely accepted mathematical theory that applies to linear systems governed by linear differential equations (Reilly et al., 1987).

Analytic element groundwater models have been used by consultants, universities, and government agencies for more than twenty years. The public domain AEM model WHAEM (USEPA, 1987) is widely used for wellhead protection and contaminant transport modeling. An enhanced version of the WHAEM model, GFLOW (Haitjema, 1995), was used for the Eagle Island application.

GFLOW is a steady-state, single layer groundwater model. GFLOW model data exists in a Microsoft Access database table and is displayed in an easy to use interface. Figure 4 shows the Eagle Island model in the GFLOW interface. The interface allows spatially referenced GIF or JPEG images, possibly created in a GIS, to be imported into GFLOW to give the modeler reference when developing the model.

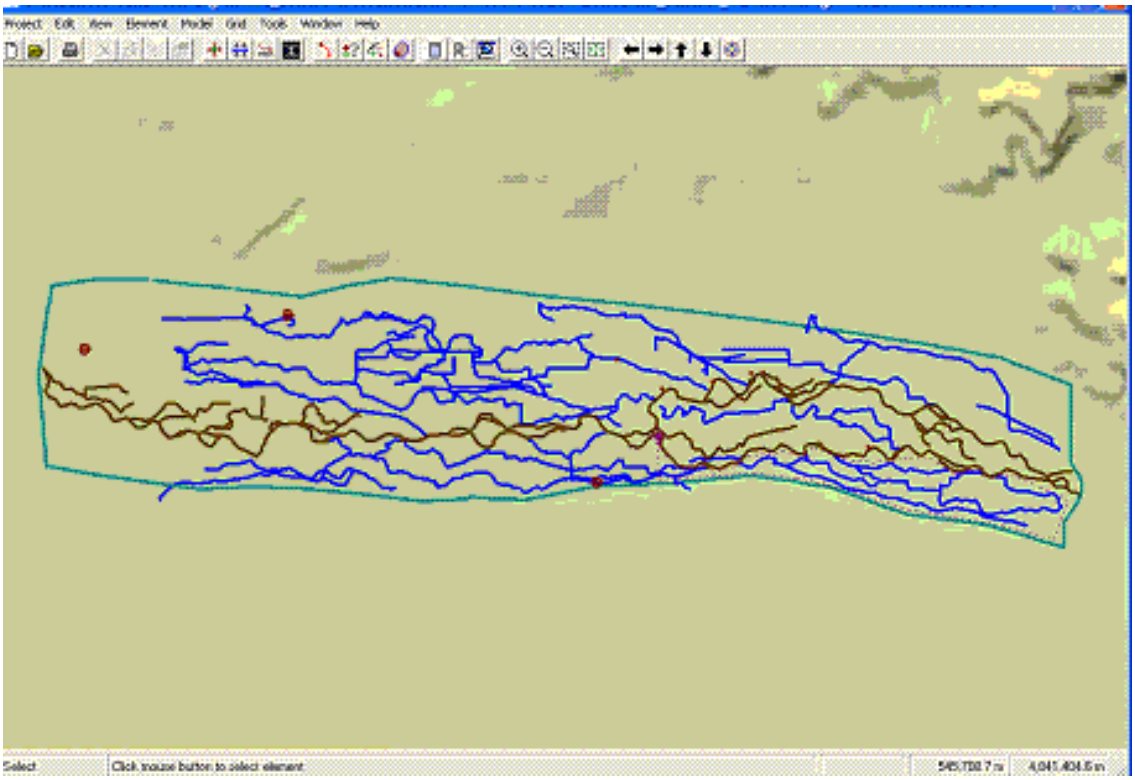

Figure 4: Eagle Island groundwater model within GFLOW interface. The green background is an image of the Boise Valley, the green lines represent boundaries, the blue lines represent canals and the brown lines represent the Boise River.

The Eagle Island AEM Model Area

Figure 5 is an aerial photograph of lands in the vicinity of the Glenwood Bridge (BIGI) to Middleton (BOMI) reach of the Boise River. The area represented in the groundwater model is outlined in red. Within the model boundary, the Boise River channels are highlighted in blue and canals are highlighted in yellow.

The Boise River splits into two channels west of the Glenwood Bridge forming an island known as Eagle Island. Known for its beauty and natural wildlife habitat, it has become a desirable site to live in the passed decade. Rapid development in the area has resulted in increased municipal groundwater pumping. River channels that outline Eagle Island are in the eastern half of the model area. Although the model domain extends as far to the west as Middleton, the model is referred to as the Eagle Island AEM model.

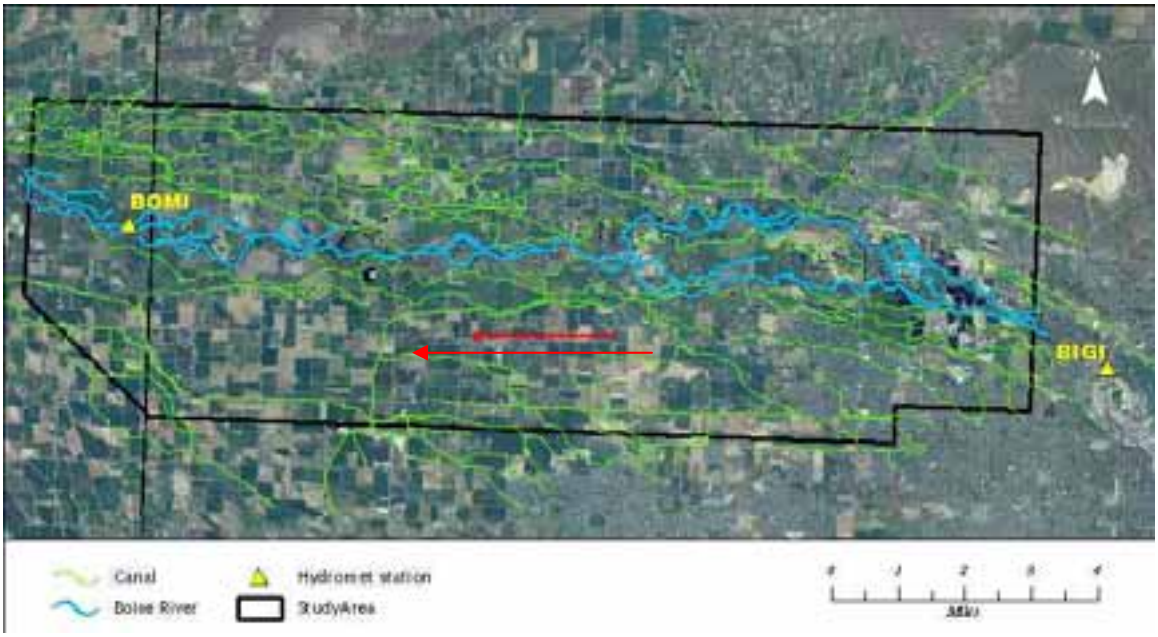

Figure 5: Aerial photo of the model area (inside black boundary). The Boise River channels are shown in blue and the canals are shown in green; the river flows from east to west as indicated by the red arrow. The river gages are indicated by the yellow triangles; BIGI is the Glenwood Bridge gage (USGS gage) and BOMI is the Middleton gage (Hydromet gage).

Methods

The Eagle Island AEM model was developed in GFLOW using data from many different sources. The model required input values to define river, drain, observation well, and boundary elements. Each element requires different information unique to itself. River elements require the head elevation at the beginning and end of a line segment in length units, the resistance (a parameter that describes the resistance to flow in or out of the element in days), the depth (the distance between the surface water elevation and the bottom of the resistance layer in length units) and the width of the river in length units. Drain elements require the same information as river elements accept for the depth. Observation well elements simply require an observed head value in length units. Boundary elements require the head elevation (in length units) at the beginning and end of a line segment. In this particular project, all of the elements were geo-referenced.

Data Collection

A variety of geospatial data were compiled and analyzed to provide input values to the

Eagle Island AEM. The model requires spatially referenced polylines that represent river and canal segments attributed with 'from', 'to' and average values for both ground elevation and head elevation for both winter and summer stages. The following geospatial datasets were used to calculate these values:

- National Hydrographic Dataset (NHD) High Resolution – NHDFlowline
- Ada County Hydrography (1:24,000)
- National Agriculture Imagery Program (NAIP) aerial imagery – mosaics for Ada and Canyon Counties
- Digital Elevation Model (DEM) mosaic derived from 2-meter LiDAR (December 2004)
- Hydromet gaging station points and stage time series data
- Canal Depth points
- Observation wells

The general strategy for preparing the geospatial input for the Eagle Island AEM involved extracting elevation values from the LiDAR DEM, deriving head and ground elevation values with respect to river and canal stage values, and joining elevation values to hydrographic line segments.

Importing GIS Data for Analytic Elements

GLFOW interface was designed to allow the modeler to draw features onto the drawing space. The user can then enter the data related to that element manually, similar to adding attributes to a feature in a GIS. If the model contains more than a few elements, this process can be very tedious.

The Eagle Island AEM model area in Figure 5 contains 2,550 superimposed analytic element features representing the river channels, canals, and drains. The model boundary itself is a far-field boundary (analogous to general-head boundary in MODFLOW) that approximates the influence of hydrologic conditions outside the model area. All of the analytic elements in Figure 5 were imported directly into GFLOW from a geo-referenced GIS database using a customized AEM utility program (Tarbet, 2004). The direct GIS linkage greatly increased the efficiency of model development and ensured that all analytic elements and model results would be geo-referenced with respect to other land-use layers.

Irrigation Season and Non-Irrigation Season Models

In order to adequately represent seasonal differences in river-aquifer interaction in the Glenwood Bridge to Middleton reach of the Boise River, two steady-state versions of the Eagle Island AEM model were developed. One version of the model represented aquifer, river, canal, and drain head conditions at the end of the irrigation season (i.e. September 2000). The other version represented those head conditions just before the start of the irrigation season (i.e. March 2000).

Far-Field Boundary Conditions

The far-field analytic element surrounding the Eagle Island AEM model area is used to approximate aquifer head conditions along the model boundary. Head conditions along the far-field boundary are adjusted in order to match the groundwater levels in three observation wells which are located just outside the model boundary (Figure 6). In the non-irrigation season model, far-field heads are chosen to match the March groundwater levels in these observation wells, and in the irrigation season model they are chosen to match the September levels. Therefore, in the vicinity of Eagle and Middleton, the far-field head conditions incorporate the localized influence of municipal groundwater pumping. At other locations on the boundary they incorporate the influence of on-farm infiltration and/or differences in topographic elevation.

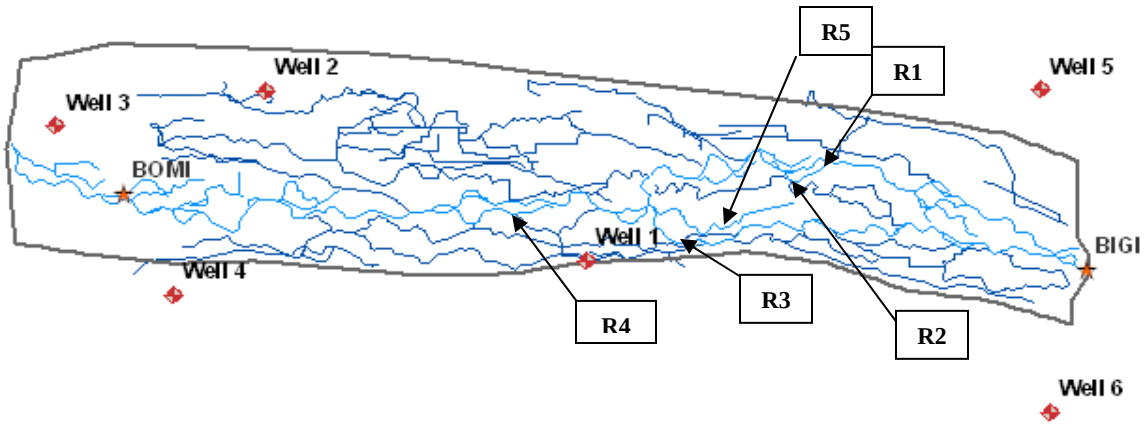

Figure 6: Map of IDWR well locations (red and grey circles) and Hydromet stations (orange stars). Boise River elements are light blue, canal elements are dark blue. The Map Numbers from Table 1 indicate where drain return flows were inserted in the river routing component of the model.

River, Canal, and Drain Boundary Conditions

The model input requirements for head-specified river, canal, and drain analytic element features includes surface-water head condition (stage), bottom elevation, width, and conductance (or resistance) of underlying bed material.

Head elevation data at “from” and “to” nodes of the Boise River polylines were extracted from the 2m DEM. River bottom elevations are calculated by subtracting the depth of water from the water surface elevation (LiDAR DEM) data. Water depth is determined by linearly interpolating stage data collected at Hydromet gaging stations at Glenwood Bridge (BIGI) and Middleton (BOMI) in December 2004 (USBR, 2006).

The non-irrigation season surface-water head conditions for river elements are determined by adding stage data from March, 2000 to these river bottom elevations. Likewise, the irrigation season river head conditions are determined by adding September 2000 stage data to the river bottom elevations.

The non-irrigation season surface-water head conditions for canal and drain elements are the LiDAR elevations for those features. The irrigation season canal and drain head conditions are the LiDAR canal bottom elevations plus water depths in canals. Canal depths were measured at 28 locations in the model area, and interpolated using an inverse distance weighting method. All canals were modeled with an average width of 2 meters, and all river channels were modeled with an average width of 30 meters.

The Boise River and canal bed conductance in the Eagle Island model was set to the same value that was used in the Treasure Valley Hydrologic Project (TVHP) MODFLOW model, i.e. 2.0 $x10^5$ square feet per day (Petrich, 2004). However, in the non-irrigation season model the canal conductance was set to zero. Bed conductance is defined as a property of the material beneath canals and rivers offering resistance to vertical flow of groundwater. During the irrigation season, when the canals are full, losses occur through the canal bottom, and bed conductance is a relevant hydrologic parameter. During the non-irrigation season, when canals function mainly as drains, and (in an unconfined aquifer) groundwater enters primarily through the sides of the canal, and bed conductance is not relevant.

Unconfined Aquifer Hydraulic Conductivity Conditions

Shallow groundwater flow in the vicinity of Eagle Island is generally assumed to be unconfined, and the aquifer thickness in the Eagle Island model is chosen such that unconfined flow conditions occur everywhere in the model domain. The only exceptions to this are in the aquifer directly beneath the river itself, where a conductance layer creates semi-confining aquifer conditions that produce river gains during the irrigation season.

Hydraulic conductivity of the aquifer in the Eagle Island model was assumed to be 144 feet/day. The value is taken from the calibrated TVHP model, and is the average hydraulic conductivities of all layer 1 MODFLOW grid cells located beneath the Glenwood Bridge to Middleton river reach (Petrich, 2004). The aquifer thickness is assumed to be 400 feet, which is the thickness of the two uppermost layers in the TVHP model.

River Routing and Surface Water Returns

A river flow routing component (between Glenwood Bridge and Middleton) is included in the Eagle Island groundwater model to ensure that the GLFOW model correctly calculates river losses. Surface water drain returns to the river occur at various locations in the Glenwood Bridge and Middleton reach and these are included in the routing flow calculation as overland flow. Table 1 shows the average return flow rates (in acre-feet per month and cubic meters per day) based on the Boise Valley water budget (USBR and IDWR, 2006). The locations of drain returns along the river are labeled in Figure 5 with the map numbers that are listed in the second column of Table 1.

Table 1: Overland flow values; see Figure 4 for Map Number locations.

	Figure 4	End of Non-Irrigation	End of Irrigation	End of Non-Irrigation	End of Irrigation
Return Flows	**Map Number**	**acre feet/m**	**acre feet/m**	**m^3/d**	**m^3/d**
Eagle Drain	R1	803	2625	33000	107926
Mason Creek	R2	3349	10486	137714	431123
North Slough	R3	1651	3052	67899	125470

Phyllis Waste	R4	290	743	11928	30529
Thurman drain	R5	472	1403	19407	57682

Model Calibration

The irrigation season version of the Eagle Island model calculates shallow aquifer head conditions within the model area, at the end of the 2000 irrigation season. The non-irrigation season version of the model calculates shallow aquifer head conditions just before the start of the 2000 irrigation season.

The Eagle Island model was calibrated by comparing irrigation season and non-irrigation season model heads to groundwater levels in three observation wells located inside the model area (Figure 6). One goal of the model is to determine if the Boise Valley water budget estimates of irrigation season and non-irrigation season river reach gains and losses are plausible, therefore, the model is not calibrated to surface flow. The observed irrigation season heads are March 2000 groundwater levels and the observed non-irrigation season heads are September 2000, levels. The observation well data was obtained from the IDWR Online Ground Water Level Database (IDWR, 2005).

Table 2 shows the irrigation season and non-irrigation season modeled and observed aquifer heads at the locations of the three observation wells located inside the model area. Using the TVHP estimates of hydraulic conductivity and bed conductance the current model heads are within a meter or two of the observed heads at all three well locations.

Table 2: Observed and modeled well heads used in calibration

Well Number	**USGS Well ID**	***irrigation season***		***non-irrigation season***	
		Obs. Head (m)	***Model Head (m)***	***Obs. Head (m)***	***Model Head (m)***
1	04N01W-22DBB1	762	762	762	762
2	04N02W-02DDD1	744	744	743	744
3	04N02W-08ADD1	734	731	733	732

Results and Discussion

Figures 7 and 8 are Eagle Island model results are displayed as a surface showing irrigation season and non-irrigation season aquifer head conditions (groundwater elevations). In both figures, the aquifer heads are highest on the east end of the model and lowest on the west end, resulting in a generalized groundwater gradient from east to west of about 0.003 meters per meter. Along the northern model boundary, the direction of groundwater flow is mostly to the southwest (toward the river). Along the southern model boundary the direction of groundwater flow is split. On the east end it is to the northwest (toward the river) and on the west end it is to the southwest (away from the river).

While the groundwater gradients in the irrigation season and non-irrigation season models are similar, there are localized differences in river, canal, and far-field boundary head conditions. These localized differences produce variations in the seasonal distribution of river (and canal) gains and losses in the Glenwood to Middleton reach. It was possible to see these localized variations only because of the high resolution elevation data used in the GFLOW AEM model.

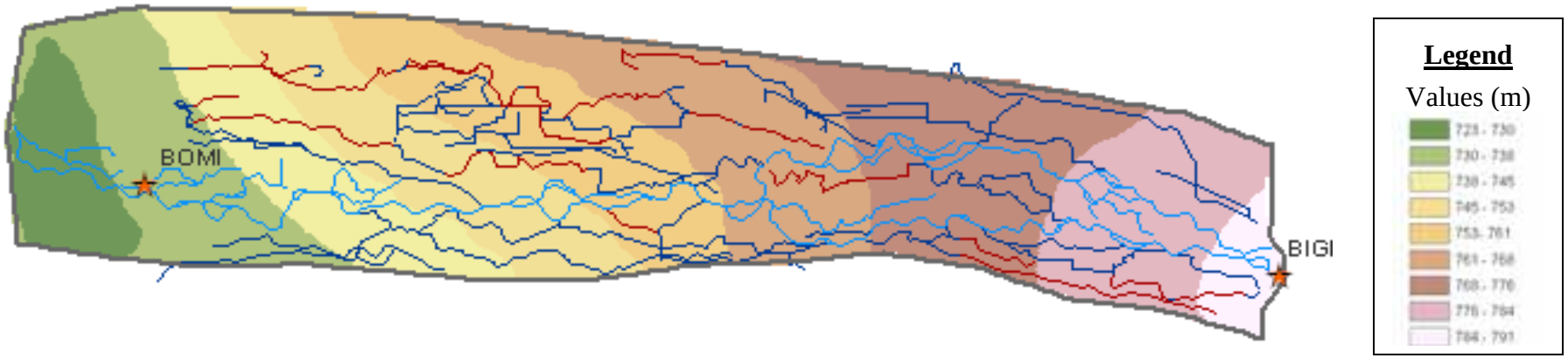

Figure 7: Irrigation season modeled aquifer head distribution; the head values are as shown in the legend (m). The Boise River analytic elements are shown in light blue and the canal elements are shown in dark blue.

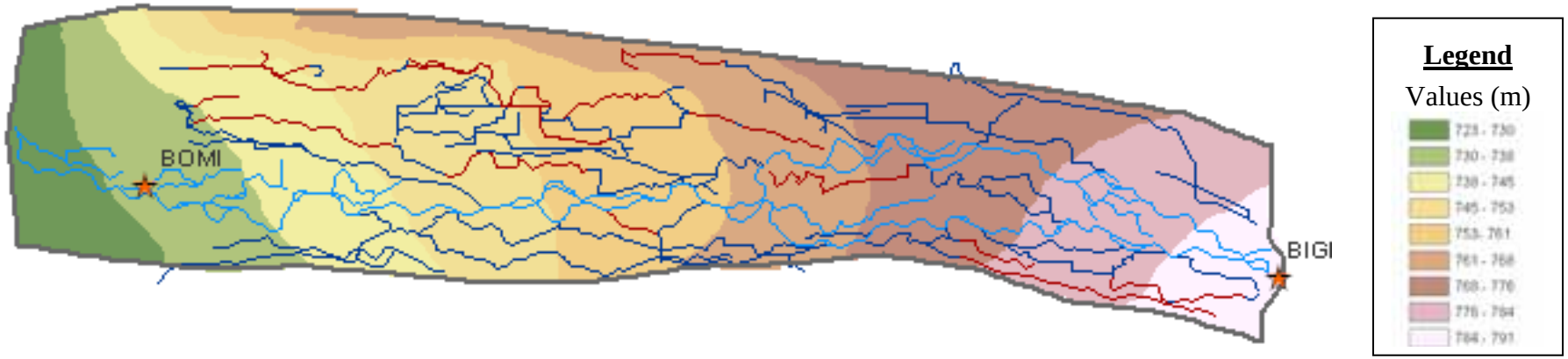

Figure 8: Non-irrigation season aquifer modeled head distribution; the head values are as shown in the legend (m). The Boise River analytic elements are shown in light blue and the canal elements are shown in dark blue.

Comparison with Boise Valley Water Budget Results

The calibrated irrigation season and non-irrigation season models produced river responses in the Glenwood Bridge to Middleton reach that were similar to the Boise Valley water budget results, i.e. a net groundwater gain to this river reach in the irrigation season, and a net loss from this reach in the non-irrigation season. However the calibrated model gains and losses were considerably smaller than those calculated in the Boise Valley water budget. The model results indicate that the gains during the irrigation season were 213 acre-feet per month and the losses during the non-irrigation season were 57 acre-feet per month.

Figure 9 shows the Boise Valley water budget estimate of average monthly river gain and loss in the Glenwood Bridge to Middleton reach over a 30 year period from 1967-1997. The average river gain during the irrigation season in the Glenwood Bridge to Middleton reach is 9,134 acre-feet per month, and the average river loss during the non-irrigation season is 5,389 acre-feet per month.

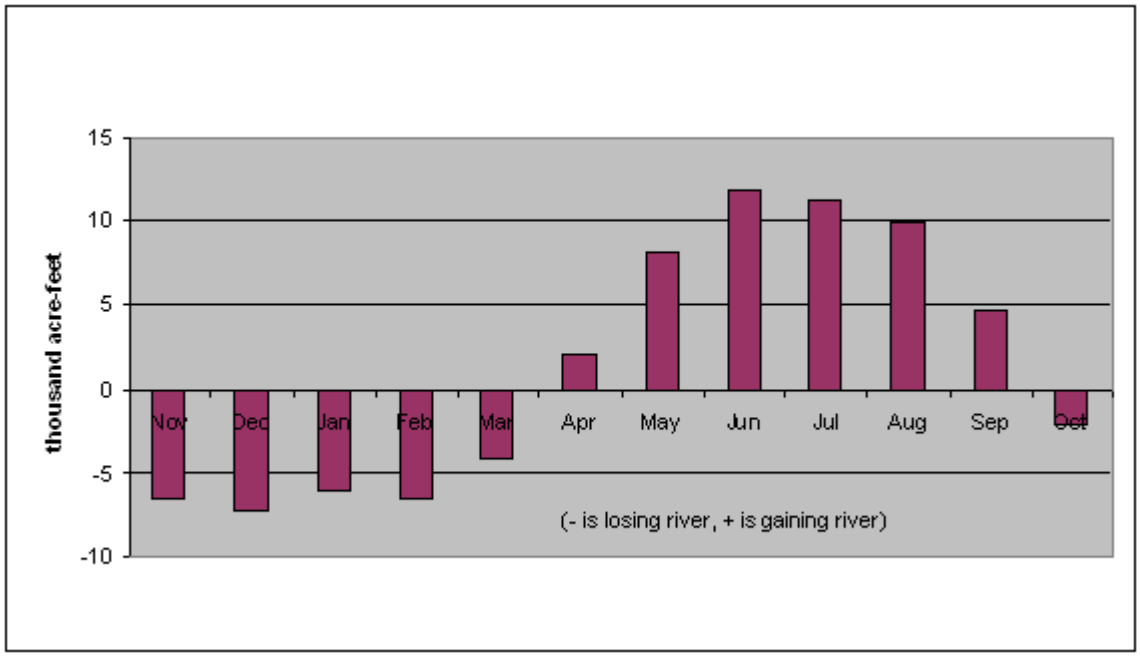

Figure 9: Boise Valley budget estimate of average monthly gain and loss (to the aquifer) in the Glenwood Bridge to Middleton reach

The magnitude of river gains and losses in the Eagle Island model depends largely on

river bed conductance, which was taken from the TVHP MODFLOW model. The TVHP model cell size was one square mile. In the TVHP model, the entire Eagle Island AEM model would be represented by 18 MODFLOW grid cells. The TVHP model used a single average river bed conductance value for all Boise River model cells, although in actuality bed conductance could be expected to vary over the length of the river (Petrich, 2004).

In order to more closely match the water budget estimates of river gain and loss, conductance in the Eagle Island model was increased two orders of magnitude, to 2.0 $x10^7$ square feet per day. Conductance of aquifer materials (like permeability) tends to be log-normally distributed (Freeze and Cherry, 1979), so it is not unreasonable to expect variations of this magnitude.

The increased river conductance produced reach gains in the irrigation season model of 12,319 acre-feet per month, and reach losses in the non-irrigation season model of 9,216 acre-feet per month (compared to averages of 9,134 acre-feet per month, and 5,389 acre-feet per month for the water budget). The change in conductance did not measurably affect aquifer head conditions or model calibration, since the specified heads of analytic elements representing the river, canals, and the far-field boundary were not changed.

Although there are differences between model results and water budget results in terms of the magnitude of reach gains and losses, the seasonal pattern of gains and losses produced by the model (even with the original TVHP river bed conductance) matches the seasonal pattern of the Boise Valley water budget.

Hydrologic Influences on River Gains and Losses

The Eagle Island AEM model results also cast some light on why river losses are likely to occur in the Glenwood Bridge to Middleton reach during the non-irrigation season.

First, aquifer head conditions on the model boundary (which reflect seasonal groundwater elevations) are lower during the non-irrigation season. While they are not low enough to change the direction of groundwater flow away from the river, the groundwater gradient along the north and south sides of the model area is less steep compared to the irrigation season gradient. This means that during the non-irrigation season there is less groundwater flowing toward the river due to a decreased gradient.

Second, the head in the canals is lower during the non-irrigation season, and as a result some (but not all) of the canals act as drains. Instead of losing water to the shallow aquifer as they do during the irrigation season (when the head in the canal is greater than the head in the aquifer), some canals are gaining water from the aquifer.

Groundwater flow pathlines generated by the Eagle Island AEM model indicate that exchange of groundwater between the river and the canals occurs during both the irrigation season and the non-irrigation season. Flow pathlines generated using the irrigation season model indicate that most groundwater gains to the river at this time of year originate at the model boundary (i.e. in the surrounding aquifer), but that some river gains originate as losses from canals. Flow pathlines generated using the non-irrigation season model indicates that at this time of year some of the canal gains originate as river losses via the groundwater system.

Summary and Conclusions

The Eagle Island AEM model demonstrates that it is plausible for Boise River channels between Glenwood Bridge and Middleton to be gaining water from the aquifer during the irrigation season and losing water to the aquifer during the non-irrigation season. Relatively small seasonal variations in aquifer, canal, and river head conditions can cause this to occur. At the same time, some canals near the river that normally lose water to the aquifer during the irrigation season are functioning as drains (taking water from the aquifer) during the non-irrigation season.

In the absence of pumping influences, nearly all of the river and canal losses would eventually return to the river below Middleton, either as surface-water drain returns or as groundwater gains directly to the main channel of the river.

The intent of the Eagle Island AEM model was to assess the plausibility of the Boise Valley Water Budget and not to gauge the influence of groundwater pumping on Glenwood Bridge to Middleton reach gains or losses. Consequently, the influence of groundwater pumping in the vicinity of the Glenwood Bridge to Middleton reach is only roughly accounted for in this model in the far-field head boundary condition. However, the model could be enhanced to explicitly include the effects on reach gains and losses of nearby groundwater pumping. This would require an expansion of the current model

domain north and south of the river, and the inclusion of several new well elements in the model. Such a model enhancement would allow for a better understanding of impacts of municipal groundwater withdrawals on gains and losses in the Glenwood Bridge to Middleton river reach.

The resolution of the Eagle Island AEM model solution allowed interaction between the Boise River and the canals to be observed. It would not have been possible to obtain the same results using the TVHP MODFLOW model because of the resolution of the grid. In addition, the integration of GIS data with an AEM model increased the time by which the solution could be obtained.

Acknowledgments

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End Notes

[i] Distributed-parameter refers to the fact that the water budget is divided into each entity that may be taking water in or out of the aquifer (e.g. rivers, precipitation, evapotranspiration, etc.) and each entity is geographically referenced,

[ii] The description of the Glenwood Bridge to Middleton river reach being a gaining or losing reach is purely with respect to the shallow aquifer interaction with the main channels of the Boise River, and not with respect to surface water returns from drains.

[iii] A steady-state solution is a hydrologic outcome that is no longer changing with time.

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