THESIS

COMPARISON OF THE GLOVER-BALMER SOLUTION WITH A CALIBRATED GROUNDWATER MODEL TO ESTIMATE AQUIFER-STREAM INTERACTIONS IN AN IRRIGATED ALLUVIAL VALLEY

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ABSTRACT

COMPARISON OF THE GLOVER-BALMER SOLUTION WITH A CALIBRATED GROUNDWATER MODEL TO ESTIMATE AQUIFER-STREAM INTERACTIONS IN AN IRRIGATED ALLUVIAL VALLEY

In many alluvial valleys wherein streams are hydraulically connected to the aquifer system, understanding and quantifying the impact of aquifer stresses (e.g. pumping, injection, recharge) on streamflow is of primary importance. Due to their relative simplicity and straightforward application, analytical models such as the Glover-Balmer solution often are employed to quantify these impacts. However, the predictive capacity of such models in intensively-irrigated systems, wherein canals, spatially-varying irrigation application patterns, and spatially-variable aquifer characteristics are often present, is not well known. In this study, the Glover-Balmer solution is compared to a calibrated MODFLOW-UZF numerical model for a study area within the Lower Arkansas River Valley in southeastern Colorado, USA. Comparison is made by simulating field-scale water extraction, addition, and fallowing scenarios, and comparing the predictions by both models of stream depletion or accretion. To create an ideal comparison, inputs to the Glover-Balmer model (stress, aquifer parameters) are obtained from the calibrated numerical model. Results for a few fallowing scenarios and from 52 extraction and addition scenarios from a variety of distances from the Arkansas River show that, under certain circumstances, the two models have good agreement in results, particularly in regions close (< about 0.5 to 1 km) to the river. However, due to aquifer heterogeneity and the overall hydrologic complexity in the natural system, results of the two models often diverge, with the Glover-Balmer model typically estimating greater impacts on the stream than the MODFLOW-UZF model. Suggested considerations are given for applying the Glover-Balmer solution, including the consideration of hydrologic components that may intercept or contribute to groundwater flow (such as irrigation canals, upflux to ET, groundwater storage, and tributaries), the potential influence of unsaturated zone processes, and changes in depletion/accretion locations and timing due to aquifer heterogeneity.

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INTRODUCTION

1.1 Background and Motivation

Water shortages caused by drought and increased water demand create stresses on agriculture, municipalities, and industries dependent on consistent water supplies in semi-arid regions such as the western United States (Hardin, Sangoyomi, and Payton, 1995). The vast majority of accessible freshwater is stored in pore space in groundwater aquifers, which have been important for civilizations throughout history (Fritts, 2013). In recent decades, the predominant means of providing access to groundwater has been through pumping, sometimes resulting in the significant depletion of water reserves (Konikow and Kendy, 2005). Though pumping wells increase economic utility in certain areas, the flow regimes and recharge patterns of surface water networks and aquifers are also affected. A literature review provided by Poff, et al. (1997) summarizes studies of the hydrologic and geomorphic alterations caused by various hydraulic structures. Poff et al. (1997) note that groundwater pumping, for example, creates a lowered water table and can cause streambank erosion due to reduced vegation stability.

Ample and accurate data regarding water systems can be employed by relatively accurate methodologies and models to quantify water resources and predict impacts to the natural systems brought about by alternative water management regimes (Arabi et al., 2006). Sufficient accuracy can be decided on a case-by-case basis by practitioners. Theis (1935) began studying the effects of groundwater pumping in relation to water table drawdown, and eventually addressed how pumping can affect stream systems by depletion (Theis, 1941). This recognition of the interconnectedness between groundwater and surface water has created the need to utilize methods and data that will account for groundwater – surface water interactions. These methods and data can quantify aspects of the natural system and be employed to guide management decisions. Figure 1.1 shows some important groundwater processes and the relative timescales.

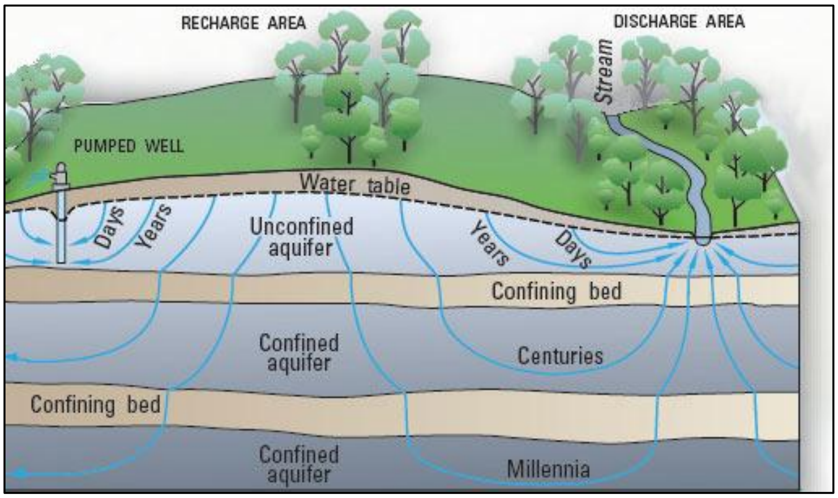


Figure 1.1. Depiction of common groundwater interactions and timescales. (water.usgs.gov/edu/watercycledischarge.html, accessed 20 June 2014)

Figure 1.1 depicts the general effect of groundwater pumping on aquifers and show that it can also influence the stream. Depletion to streams induced by groundwater pumping has lead to the creation of analytical methods for estimating depletion by Theis (1941), Glover-Balmer (1954), and Jenkins (1968a), and others. Continued use of analytical solutions in has lead to their evaluation by Spalding and Kahleel (1991), Sophocleous et al. (1995; 2005), Hunt et al. (1999), Nyholm et al. (2001), and others. These studies have compared the older analytical solutions from Glover-Balmer and Jenkins (1968a) to more recent analytical solution or hypothetical groundwater models, but have not compared them with an extensive, transient, three-dimensional, regional groundwater model calibrated to field data; nor have they explored the effects groundwater pumping at relatively large distance from the stream network, and such concerns serve as the motivation for this study.

1.2 Objectives of Thesis

A commonly employed method for estimating stream depletion or accretion due to groundwater pumping or injection, respectively, is the Glover-Balmer (1954) analytical solution. The Glover-Balmer solution was derived from the Theis (1941) solution, which relates aquifer piezometric head drawdown to a pumping rate and aquifer parameters. The Glover-Balmer solution and other analytical methods such as the Jenkins (1968a) method, a simplification of the Glover-Balmer solution that employs a stream depletion factor (SDF), and the solution developed by Hantush (1965), which incorporates a semi-pervious streambed and partial stream penetration, are commonly employed because aquifer parameter data are often sparse and simplifying assumptions imposed by analytical solutions make estimation possible.

Previous studies have described potentially large discrepancies between the Glover-Balmer solution and newer analytical solutions or numerical models. The continued use of the Glover-Balmer solution in practice creates an impetus to compare it to a numerical model calibrated to data from a real system. In this study, the ability of the Glover-Balmer solution to reasonably estimate aquifer-stream interaction due to altered field water management in an irrigated alluvial valley is assessed by comparison to a calibrated, three-dimensional, transient MODFLOW-UZF groundwater model, developed for a 50,600 ha study area, referred to as the Upstream Study Region (USR) within the (Lower Arkansas River Valley) LARV in southeastern Colorado. The comparison of the two models allows one to determine how significantly stream depletion/accretion estimates from the Glover-Balmer solution deviate from the calibrated

MODFLOW-UZF model, which is assumed to more accurately model the natural system. The USR is assumed to be more accurately modeled by the MODFLOW-UZF model through its estimation of more complex, transient and three-dimensional groundwater flow equations, evapotraspiration (ET), seepage to and from tributaries and irrigation canals, and individual irrigation events and crop patterns. This is all validated by the use of extensive calibration and testing using validated procedures and data sets. Previous studies have made similar efforts to compare analytical and numerical models, but have not applied a regional scale model that is calibrated to data from a real system. Once differences in stream depletion/accretion estimates between the MODFLOW-UZF model and the Glover-Balmer solution are observed, the next step is to examine the possible causes. The regional scale model allows one to determine which hydrologic components considered by the MODFLOW-UZF model (and not by the Glover-Balmer solution) are significantly influenced by altered field water management, and thus, cause the two models to yield different stream depletion/accretion predictions. Figure 1.2 presents the study location within Colorado, and also depicts the stream network, irrigation canal system, irrigated fields, pumping well locations, and towns.

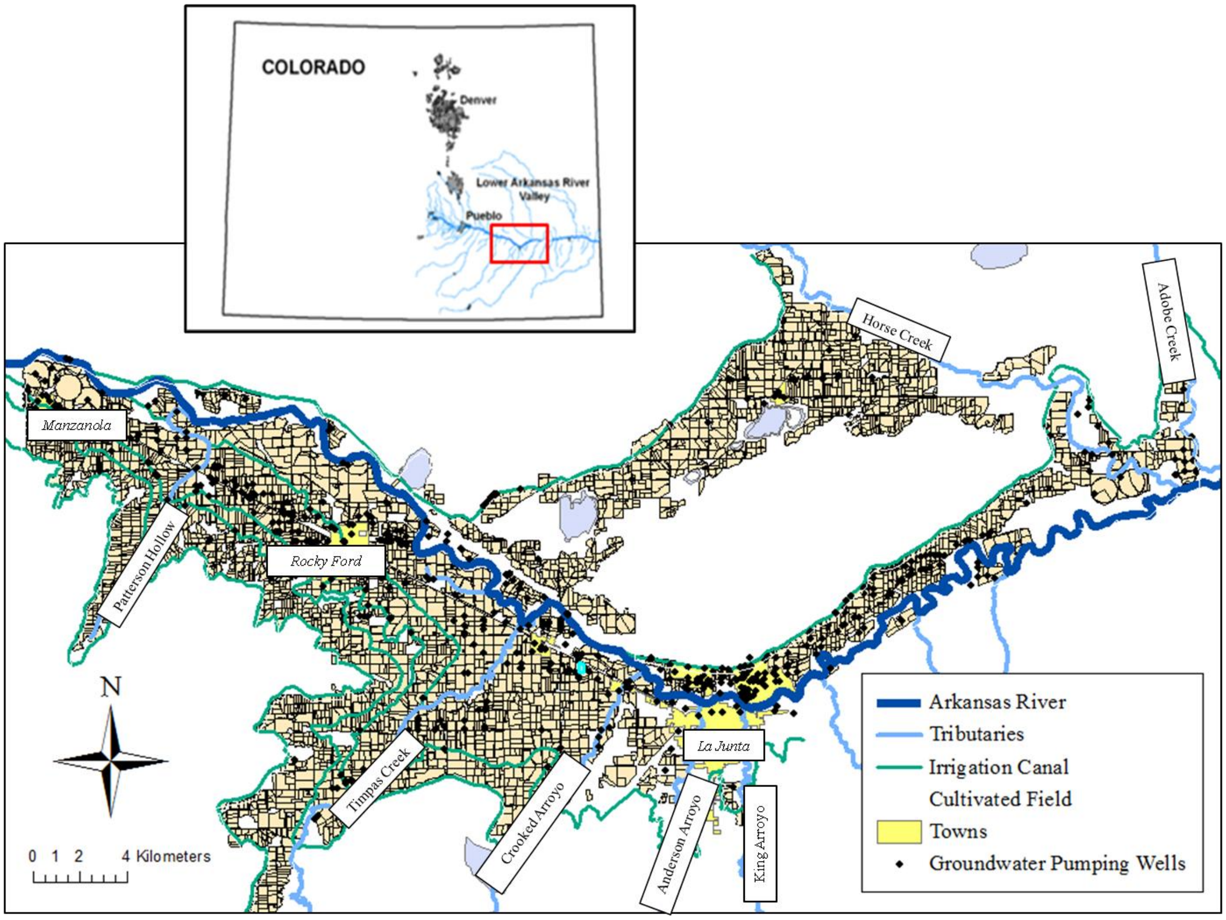


Figure 1.2. The Upstream Study Region within Colorado's LARV.

The MODFLOW-UZF model simulates irrigation patterns based on crop type and canal flowrate data, canal seepage, unsaturated zone flow processes, seepage to and from the stream network, evapotraspiration (ET) from the unsaturated zone, upflux to ET from the saturated zone, layer-averaged groundwater flow and hydraulic head in the saturated zone, and maintains a water balance to provide further accuracy. Scenarios investigated include four lease-fallowing (three-year and one-year fallowing durations), 52 water addition to the saturated zone, 49 water addition to the ground surface, and 52 water extraction from the saturated zone. The stress duration for all water addition and extraction scenarios is one month.

1.3 Organization of Thesis

First, the development of analytical models used for the estimation of stream depletion due to well pumping is reviewed and discussed, including the Glover-Balmer solution and its application for this study. This is followed by a review of the development of the MODFLOW finite-difference numerical model, and previous studies of comparisons between analytical and numerical models in estimating stream depletion due to well pumping. Next, the methodology applied in this study is presented, including a description of the study area, the use of the MODFLOW-UZF model developed for the LARV, and the method used to compare the Glover-Balmer solution to the MODFLOW-UZF model. Results are presented for the four scenario types considered: lease-fallow, water addition to the saturated zone, water addition to the ground surface, and water extraction from the saturated zone. Finally, the conclusions and implications are discussed.

LITERATURE REVIEW

To provide a basis of information on which the methodology employed in this study was developed, this chapter will provide a review of the development of early analytical solutions, a brief review of the capabilities of a finite-difference numerical model and the development of the MODFLOW three-dimensional finite-difference groundwater model application for the LARV, and studies that have evaluated the accuracy of analytical solutions using field data, a comparison to a numerical model, or a comparison to another analytical model.

2.1. Analytical solutions for estimating stream-pumping well interactions

The analogy developed between the theories of heat transfer and aquifer hydraulics was employed by Theis in 1935 to develop a relationship between well discharge and the lowering of the piezometric surface in a confined aquifer (Theis, 1935).

$$s(x,t)= \frac{Q}{4\pi T} W(u) \tag{1}$$

Where Q is the pumping rate (m^3/s), T is aquifer transmissivity (m^2/s), s is drawdown (m), x is distance from the well (m), t is the pumping duration (s), and W represents the well function which is a function of the pumping rate and aquifer parameters. The input into the well function, u, can be defined as:

$$u(x,t)= \frac{x^2 S}{4 T t} \tag{2}$$

Where S is aquifer storativity (unitless) and all other variables are consistent with those defined following Eq. (1).

In 1941, Theis also recognized that pumping wells can alter head gradients and deplete nearby streams (Theis, 1941). The efforts by Theis created the ability to begin estimating the effects of pumping wells on nearby streams quantitatively. Following the development of Theis' equation for estimating drawdown due to well pumping, Cooper and Jacob created a graphical method for estimating the Theis equation (Cooper and Jacob, 1946). The solutions from Theis and Cooper-Jacob served as a basis for the understanding of the effects of well pumping on streams, but normally are not applied in practice or evaluated in studies. Although the Glover-Balmer (1954) and Jenkins SDF (1968a) solutions make many of the same assumptions as the Theis (1941) and Cooper-Jacob (1946) solutions, the Glover-Balmer and Jenkins SDF solutions have grown to be much more popular in practice and policy.

2.1.1. The Glover-Balmer solution

The Glover-Balmer solution was derived from the Theis (1935) equation in 1954 by Robert E. Glover and Glenn G. Balmer as a way to estimate stream depletion due to well pumping by multiplying the pumping rate by a factor based on the complimentary error function, aquifer parameters, and distance from the stream. In fact, it can be seen that the terms within the square root are the same at those found in Eq. (2).

$$Q_r = Q\left[erfc\sqrt{\frac{S}{4T}\frac{x^2}{t}}\right] \tag{3}$$

Where S is storativity, T is transmissivity (m^2/s), x is the straight-line distance to the stream (m), t is the pumping duration (s), Q is the pumping rate (m^3/s), and Q_r is stream depletion (m^3/s). Several simplifying assumptions are imposed in order to derive Eq. (3), including a semi-infinite, homogeneous, and isotropic aquifer, a perfectly straight stream, perfect connection between the stream and aquifer, and constant stream stage over time. It is also assumed that water is instantaneously released from aquifer storage, that the aquifer receives no recharge, the water table is initially horizontal, and that the stream water temperature is constant and equal to that of the aquifer. These assumptions also are applied in the case of water injection; the only difference is a change in the direction of flow, meaning water moves from the well to the stream.

The assumptions inherent in the Glover-Balmer solution greatly simplify natural groundwater systems. Most groundwater systems have a certain degree of heterogeneity, anisotropy, limiting and non-linear boundaries, partial stream connection, and have fluctuating water table elevations and gradients over time. Thus, it is by considering the complex, cumulative effects of the hydrologic components considered to be negligible by the Glover-Balmer solution that leads one to question its accuracy. This study and others described in Section 2.2 show that these assumptions can certainly over-simplify the natural system. However, one can observe that all analytical and numerical models of natural systems simplify reality to varying degrees. Yet the assumptions made by the Glover-Balmer solution simplify reality to a much greater degree than that of a three-dimensional, calibrated and tested, transient numerical model like the MODFLOW-UZF model applied in this study. For this reason, the numerical model is used to estimate the significance of the assumptions made by the Glove-Balmer solution.

The Glover-Balmer solution has been chosen for this study due to its extensive use within Colorado and the midwestern United States. Conversations with many engineers working in

Colorado in the Arkansas River Valley (Ivan Walter, Dan Niemela, Craig Lis), as well as state officials such as Bill Tyner (Assistant Division Engineer, Colorado Division of Water Resources) and Andy Moore (Water Resources Engineer, Colorado Water Conservation Board) have revealed the Glover-Balmer solution to be generally accepted for many surface water programs, groundwater programs, and transactions overseen by the state of Colorado. Many examples of technical reports describing estimations made using the Glover-Balmer solution in Colorado can be found, like the one made by Stephen Sonnenberg & Associates and the URS Corporation (Stephen A. Sonnenberg & Associates and URS Corporation, 2010) reveal continual use of the Glover-Balmer solution in practice. Furthermore, Miller et al. (2007) mention various legal rulings in which the Glover-Balmer solution was accepted for use, which indicates that it will continue to be supported legally. Similarly, Young (2014) describes the extensive use of the Glover-Balmer solution for policies. Sophocleous et al. (1995; 2005) suggest the continued use of the Glover-Balmer solution by mentioning its use within policies implemented in Kansas. The development of a new analytical solution by Zlotnik and Huang (1999) and its use in evaluating older analytical models suggests the extensive use of the Glover-Balmer solution and other analytical methods in Nebraska. Another benefit in studying the Glover-Balmer solution is that conclusions drawn from this study will be applicable to the Jenkins SDF method. Miller et al. (2007) note the use of SDF factors in Colorado, and Young (2014) notes its continued use in Kansas.

Though initially developed to assess well pumping, the Glover-Balmer solution also can be used to estimate accretions from recharge ponds and injection wells by supplying a negative pumping rate. The Environmental Protection Agency (EPA) monitors injection wells used for aquifer recharge, storage, and recovery. Figure 2.1 displays the number of such wells in the United States as of 2009.

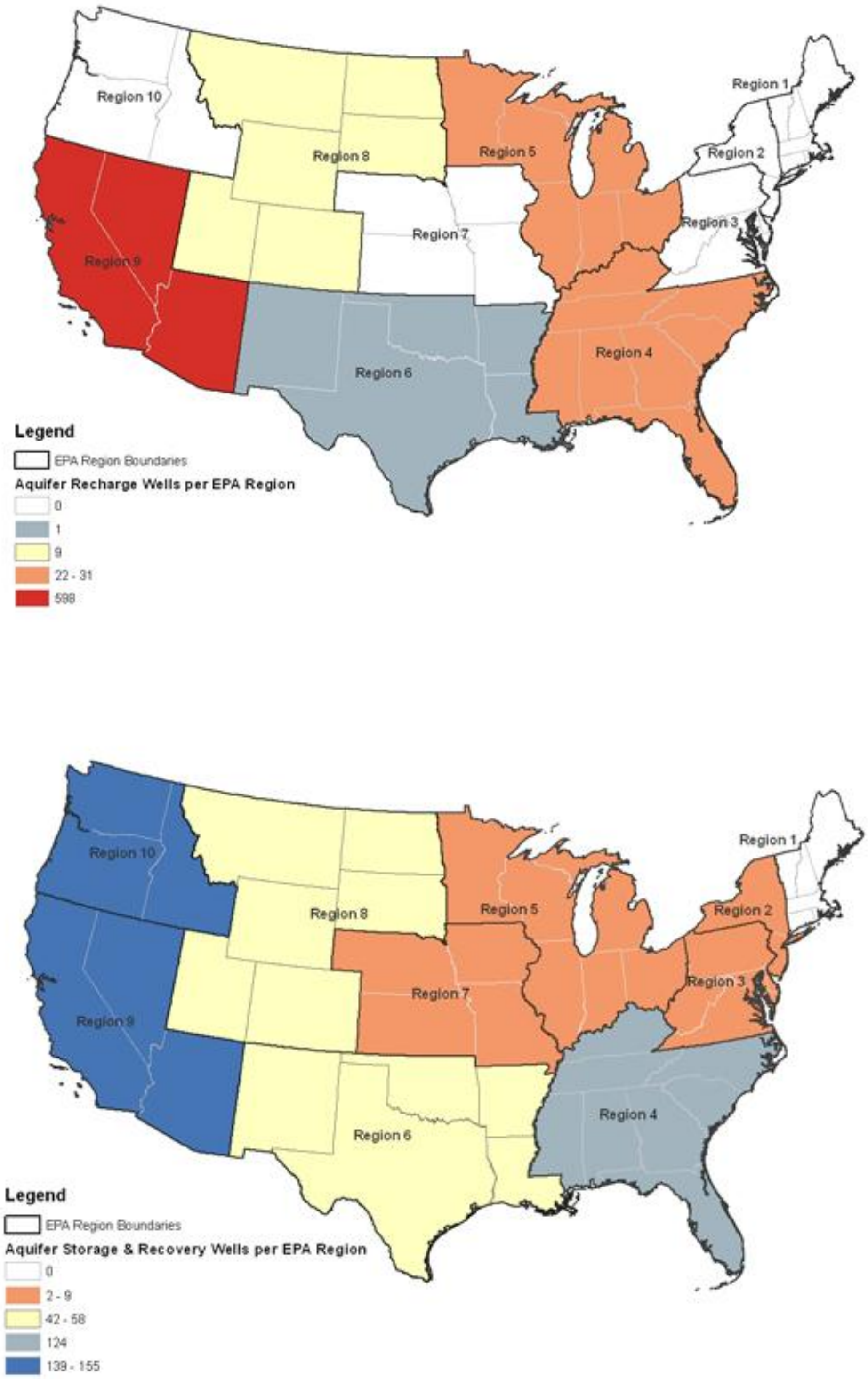


Figure 2.1. The number of (A) aquifer recharge, and (B) aquifer storage and recovery wells within each EPA region in 2009 (water.epa.gov/type/groundwater/uic/aquiferrecharge.cfm, accessed 20 June 2014).

The United States Geological Survey (USGS) also describes many aquifer recharge projects throughout the United States (http://water.usgs.gov/ogw/artificial_recharge.html), though they are not limited to injection wells. A feasibility study was conducted on the Platte River in Nebraska in which recharge ponds would be constructed and return flows to the stream as groundwater seepage would be estimated using the Jenkins SDF method (Platte River Recovery Implementation Program Office of the Executive Director et al., 2010). Additionally, a study for the Lower Arkansas Valley Water Conservancy District showed that many ponds used to supply irrigation systems in the LARV are losing significant volumes of water as infiltration to the aquifer (Woodka, 2013). It is through consideration of such topics and concerns that motivates the water injection scenarios described in this study. Results from this study could help guide current and future use of the Glover-Balmer solution for considerations of recharge to the aquifer via injection wells and pond infiltration.

The Glover-Balmer solution considers a pumping well as an infinitesimally small point at which water is exchanged with the aquifer. This differs from the mechanism (discussed in more detail in section 3.2) utilized by the MODFLOW-UZF model developed for the LARV where the flux imposed by a pumping well is applied to one of the 62,500 m^2 model cells. When compared to other differences between the Glover-Balmer solution and MODFLOW-UZF model, this difference is expected to be negligible.

2.1.2. Analytical models developed after the Glover-Balmer solution

Jenkins' development of the SDF in 1968 builds upon the Glover-Balmer solution and attempts to account for variable parameters such as transmissivity and boundary conditions (Jenkins, 1968a; 1968b). Jenkins defines the SDF as the time when 28% of the pumping rate is being supplied as stream loss, and can be depicted by an ideal response curve for stream depletion rate and volume (Jenkins, 1968a ; Miller et al., 2007). Though the use of 28% is arbitrary (Jenkins, 1968a), the SDF parameter is derived from a model and attempts to improve upon the accuracy of aquifer parameters utilized by the Glover-Balmer solution. Compared to the other analytic solutions described in Chapter 2, the Jenkins SDF method is utilized in practice relatively extensively. In studying the Glover-Balmer solution it is possible to glean some insight into the efficacy of the Jenkins SDF method since it is derived from the Glover-Balmer solution.

In an effort to improve existing analytical solutions and more accurately model natural systems, Hantush developed an analytical solution which accounts for a semipervious stream bed and partially penetrating aquifer (Hantush, 1965). Though Hantush's equation may more accurately model real systems, it has been less popular in practice than the simpler solutions provided by Glover, Balmer, and Jenkins. Hantush's solution makes many of the same assumptions as the Glover-Balmer solution, such as a semi-infinite aquifer, homogeneous and isotropic aquifer materials, and a perfectly straight stream. An analytical solution for estimating drawdown in an unconfined aquifer was created by Neuman through analysis of aquifer tests and physical drawdown measurements (Neuman, 1972; 1974; 1975). Neuman's solution, developed for fully-penetrating monitoring wells, employs the well function including T, S, S_y and the option to include vertical and horizontal hydraulic conductivity if delayed responses are considered. This option differs from the other analytical solutions in that it attempts to account for vertical and horizontal conductivity, which tend to be quite different (Fritts, 2013).

The more recent analytical solutions attempt to model stream-aquifer interactions more realistically while retaining the simplicity and ease-of-use of initial analytical solutions. The solution developed by Hunt (1999) incorporates streambed clogging and a linear relationship between seepage outflow and the change in piezometric head across the clogging layer (Hunt, 1999). This solution was in response to studies like that of Sophocleous et al. (1995), which found that the assumption of perfect conductance between the stream and aquifer made by the Glover-Balmer solution can lead to significant errors in comparison to errors from the other assumptions evaluated. Hunt's solution also assumes that streambed penetration and cross-sectional area are relatively small. The solution retains other assumptions consistent with the Glover-Balmer solution, including a much smaller vertical velocity than horizontal velocity (Dupuit assumption), a semi-infinite, homogeneous and isotropic aquifer, small drawdown compared to aquifer thickness, a constant pumping rate, and that stream stage is constant.

Like the solution from Hunt (1999), a solution developed by Zlotnik and Huang (1999) also incorporates the effects of a partially penetrating stream and semi-conductive streambed. Unlike Hunt's solution, however, Zlotnik and Huang were able to account for stream width. This solution can better model relatively shallow, wide streams, where the assumptions made by older analytical solutions of perfect stream-aquifer connection and total penetration by the stream down to bedrock would be unacceptable. Zlotnik and Huang were able to compare their solution to the Theis (1941), Glover-Balmer (1954), and Jenkins (1968a) methods to determine that the stream-aquifer interface parameter, incorporating the effects of hydraulic conductivity and thickness of streambed sediments, and stream width are quite sensitive and play an important role in stream-aquifer interactions. Work by Butler et al. (2001) resulted in another solution which accounts for finite width, small stream penetration, and an aquifer of limited lateral extent. Such a solution improves on the assumption of semi-infinite aquifer extent, which can be an unacceptable assumption for certain aquifers that are long and narrow, for example. When compared to the Glover-Balmer (1954) and Hantush (1965) solutions, Butler et al. (2001) noted not only that streambed conductance plays a significant role in estimations, but that distance from the stream is also important. The study by Butler et al. (2001) is the only one in which sensitivity to distance from the stream was explored, besides the study described by this thesis. The sensitivity to distance from the stream found by Butler et al. (2001) is consistent with some of the findings in this thesis, and will be discussed in more detail in Chapters 4 and 5.

Before discussing the development and advantages of numerical models, it is important to consider the reasons for which analytical solutions have remained popular through current times. Analytical solutions were created at a time in which groundwater science and computational capabilities were less developed than today. Additionally, the onset of computers with ever-increasing computational power has created the ability to create more complex and accurate models. Yet, in accompaniment to complexity is the need for much larger amounts of data. Conversations with the engineers and state officials mentioned earlier in Chapter 2 have revealed a preference for analytical solutions like the Glover-Balmer solution because they can make stream depletion/accretion estimations with relatively small amounts of data. And in practice, data often are quite sparse and analytical solutions become the only viable option. Analytical solutions are also simpler, and can save significant amounts of time in conducting studies in practice. However, despite the many advantages of analytical solutions, it is important to attempt to evaluate their efficacy. In the case of the LARV, ample data have been obtained to develop a relatively accurate numerical model, allowing one to gain insight on the Glover-Balmer solution. The accuracy of the numerical model has been evaluated during the calibration and testing process, and is summarized in Section 2.2.

2.2. *Development of the MODFLOW finite-difference groundwater model*

The MODFLOW groundwater flow model was originally published in 1984 by the USGS, and has seen four major releases since then (McDonald and Harbaugh, 2003). The most current release is MODFLOW-2005, which is the version applied in the model for the LARV. The software is open-source, and has become one of the most familiar and popular groundwater models in the world (McDonald and Harbaugh, 2003). Although originally designed solely for estimation of groundwater flow, the MODFLOW model now has the capacity to incorporate numerous equations to account for other hydrologic processes. These sets of equations are called "packages". The packages utilized in the MODFLOW model employed in this study are the RIV package for estimating irrigation canal seepage and river seepage, and the UZF1 package for estimating unsaturated zone flow processes.

Before describing the MODFLOW-UZF application for the LARV, consideration is given to other computational models based on physical data. Examples are limited to applications for reduction of waterlogging and salinization, which is the original context for which the MODFLOW-UZF model was developed for the LARV. International examples include those by Schoups et al. (2005a) in the Yaqui Valley of Mexico, who applied a hydrologic/agronomic model coupled with an optimization model to investigate crop yields in relation to groundwater resources and drought; Xu et al. (2010), who explored options for relieving waterlogging and salinization in the Yellow River Basin in China through altered irrigation management and infrastructure alternatives through the utilization of a lumped-parameter model; efforts in India by Singh et al. (2006) exploring methods for reducing salinity and waterlogging with a hydrological model; and Kumar and Singh (2003), who studied water-management scenarios with the purpose of reducing waterlogging using a calibrated and tested model. An example from the United States involves efforts in the San Joaquin Valley in California where Gates and Grismer (1989) and Gates et al. (1989) applied a groundwater flow and salt transport model to develop strategies that combined economically optimal irrigation and drainage strategies. Another example from this region involves Schoups et al. (2005b), where a regional-scale model including reactive salt transport and flow in the unsaturated and saturated zones simulates salt concentrations over a 57 year period in both the shallow and deep aquifers.

Much of the following information regarding the development and function of the MODFLOW-UZF model is summarized from Morway et al. (2013), and readers are encouraged to visit that publication for more details. The MODFLOW-UZF application for the LARV employs the MODFLOW-NWT (Niswonger et al., 2011) version of MODFLOW (Harbaugh, 2005) for simulating three-dimensional flows in unconfined alluvial aquifers based on a finite-difference formulation and the Newton solution method. Flow above the water table is approximated using the UZF1 package for MODFLOW (Niswonger et al., 2006), which applies the kinematic-wave function to simulate one-dimensional vertical flow within the vadose zone. UZF1 also assumes that hydraulic properties are uniform within the unsaturated zone, and applies this assumption to each column beneath each grid cell.

For this study, the model for the Upstream Study Region (USR), comprised of about 50,600 ha (of which 26,400 ha are irrigated), is applied. The model boundary begins just west of Manzanola and continues eastward to Adobe Creek, which is near Las Animas (not shown in Figure 2.2), highlighted in Figure 2.2. The finite-difference computational grid is defined by dividing the alluvial aquifer into 250 m × 250 m cells, as shown in Figure 2.2. The model has 15,600 active nodes and 2 layers. The top layer has a thickness approximately 5 m, encompassing deeply-rooted crops. The lower layer extends from the bottom of the upper layer to the impervious bedrock. The simulation period for calibration and testing is 1999 – 2009 with 552 weekly time steps.

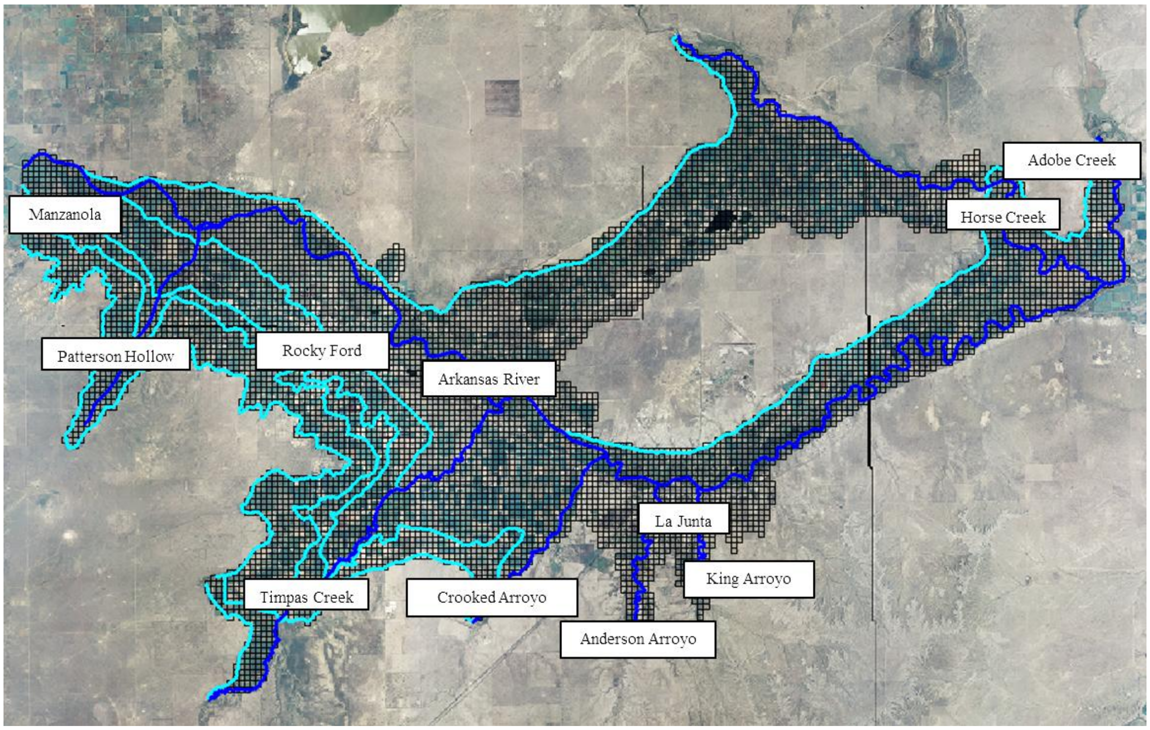


Figure 2.2. MODFLOW-UZF model cell discretization within the LARV.

During each simulation time step (week), certain fields are selected for irrigation based on a priority ranking system which accounts for crop type (meaning high priority crops, determined by farmer interviews, are irrigated before low priority crops) and whether the field was irrigated within the past few weeks or not. This ensures relatively even distribution of irrigation water, and staggers application to a different set of fields at each time step. The predominant irrigation methods are flood irrigation using surface water and sprinkler irrigation using groundwater. Findings from a study by Gates et al. (2012), in which water balance data were collected during numerous irrigation events in the LARV between 2004 and 2008, are applied to determine irrigation application volumes to each field. Water balance data are fitted to log-normal distributions, the distributions are adjusted based on crop type, and random irrigation and tailwater runoff values are selected for each field for the application period. For the study presented in this thesis, all irrigation application patterns, runoff fractions, and infiltration volumes are identical for each application of the MODFLOW-UZF model (expect for the model cell receiving an additional stress, as discussed in Section *3.2*).

The UZF1 package is applied to model unsaturated flow between the land surface and water table (Niswonger et al., 2011). The Richard's equation is solved using a kinematic wave approximation, which assumes only gravity potential gradients influence flow through the unsaturated zone and that hydraulic properties are uniform within each vertical column of model cells. The relation between water content and hydraulic conductivity is defined using the Brooks-Corey function. Residual water content is calculated by taking a difference between saturated water content and specific yield.

Related to surface irrigation, losses (seepage) from the seven irrigation canals are estimated at each time step using the MODFLOW RIV package. Simulated seepage reduces canal flowrates, which are checked against actual diversion data to maintain a water balance. The other irrigation source considered exists as well pumping. Monthly pumping volumes are obtained from the Colorado Division of Water Resources (CDWR) for all agricultural, municipal, and industrial pumping wells. Pumped water (about 5% of the total irrigation volume) is allocated to groups of fields owned or operated by a company or individual within close proximity to the well.

Precipitation data are obtained from the National Oceanic and Atmospheric Administration (NOAA), adjusted to correspond with the MODFLOW-UZF time steps and grid discretization, compared to National Weather Service and Colorado Agricultural Meteorological Network

(CoAgMet) weather stations, and adjusted if needed. Finally, it is assumed that 70% of precipitation infiltrates, and 30% runs off or is intercepted. ET estimation beings by establishing reference evapotraspiration (ET_r) values. Daily ET_r values are calculated and interpolated, and then applied to historical crop distribution patterns obtained from the Farm Service Agency (FSA). Once daily total ET values are summed to obtain weekly values, field-by-field values are converted to grid-based values. Total ET values are then compared to values estimated by Elhaddad and Garcia (2008) from satellite imagery to ensure accuracy.

Hydraulic conductivity values are assigned as part of the calibration process. Stratigraphy data from well driller logs are assigned to four material classes (gravel, sand, silt, and clay), and each class is given a range of values deemed acceptable in the literature (Domenico and Schwartz, 1998; Freeze and Cherry, 1979). Horizontal hydraulic conductivity (K_H) values are assigned to the four material classes at each borehole location, and a depth average is applied. Average K_H values are obtained for the remaining model cells using ordinary kriging. A second calibration effort, using the PEST calibration model, is applied to pilot points that are not constrained to borehole locations but are regularized by values obtained from another calibration model, UCODE. Specific yield values and vertical hydraulic conductivities in the saturated and unsaturated zones are similarly constrained using borehole data and estimated using UCODE. In order to maintain efficiency and avoid the introduction of significant non-linearity to the automated calibration process, of the six variables (hydraulic conductivity, specific yield, canal conductance, potential ET, extinction depth, and a multiplier applied to calculated vertical hydraulic conductivity) to which the model is calibrated, only hydraulic head and groundwater return flows are considered. The automated calibration process occurs from the beginning of

April, 1999 to the end of March, 2004, reserving the final portion of the simulation period for testing. The other four variables were considered during manual calibration.

Morway et al. (2013) summarize the observations used as a basis for manual calibration as, (1) measurements of canal seepage (Martin, 2013; Shanafield et al., 2010; Susfalk et al., 2008), (2) the total actual ET obtained from the RESET model using satellite imagery (Elhaddad and Garcia, 2008), (3) field estimates of groundwater ET (Niemann et al., 2011), and (4) estimates of recharge infiltration ratios (Gates et al., 2012). From these information sets, canal conductance, potential ET, extinction depth, and a multiplier applied to the saturated vertical hydraulic conductivity of the unsaturated zone are manually adjusted. Manual adjustments required judgment based on knowledge and experience regarding what is physically reasonable, as well as some recommendations from literature. Following each manual adjustment was a rerun of the automated parameter estimation, though it was found that changes to hydraulic conductivity and groundwater recharge were small. Figure 2.3 displays time- and depth-averaged transmissivity, calibrated specific yield in layer 1, and time-and depth-averaged water table elevations predicted by the MODFLOW-UZF model.

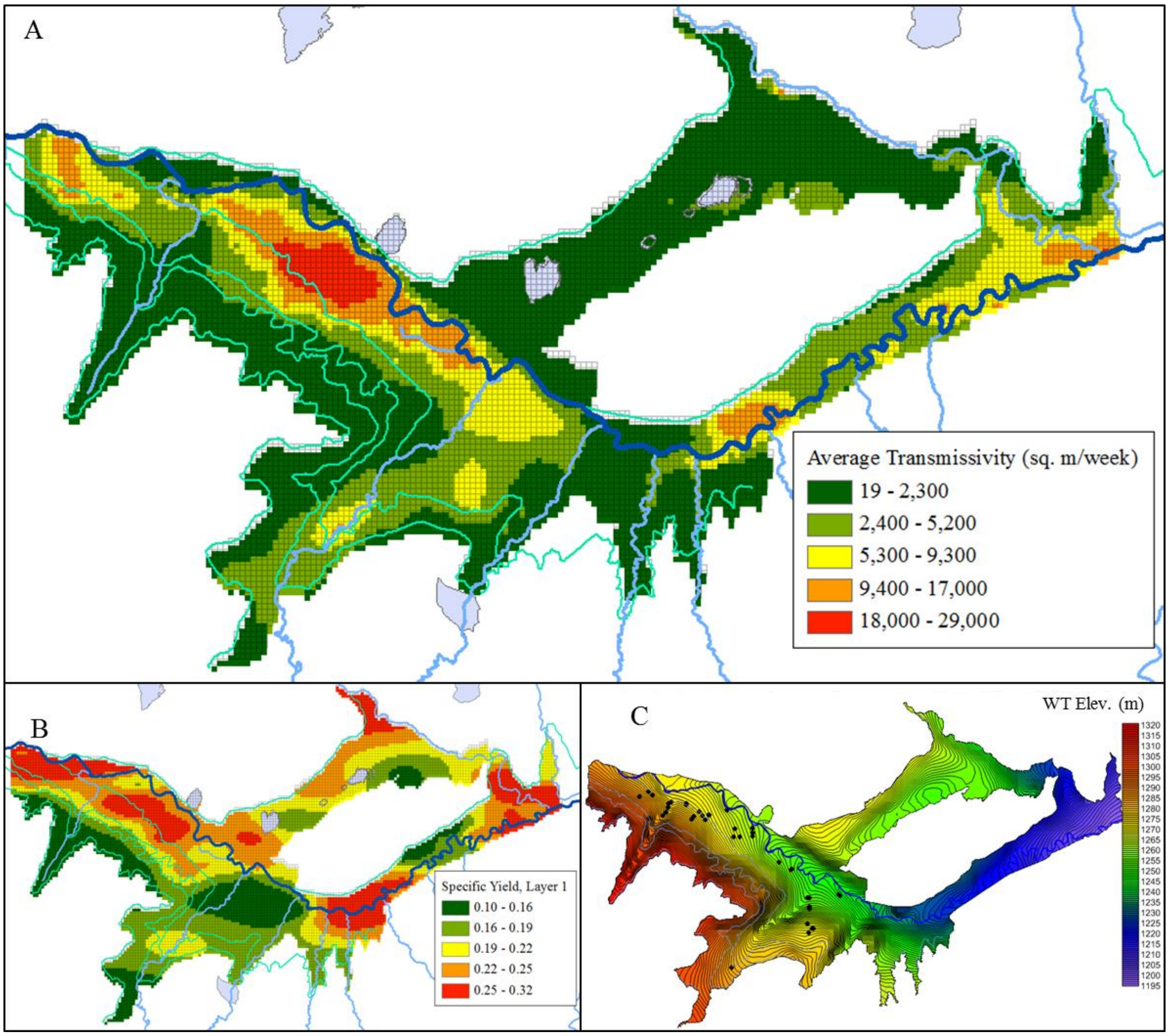


Figure 2.3. (A) Time- and depth-averaged transmissivity values, (B) specific yield for layer 1, and (C) time-averaged water table elevation.

Morway et al. (2013) describe the values of root mean square errors for each of the six variables mentioned previously. It is noted that overall return flows to the Arkansas River in the USR can become negative, indicating a net loss in water from the Arkansas River. The authors mention that this is realistic, as pumping wells could induce losses from the river during certain periods. This observation provides support for some of the conclusions from the study outlined in this thesis. The authors also note several areas of uncertainty that can lead to large variability in return flow estimations, including errors in historical cropping patterns which guided simulated irrigation application, significant variability in irrigation practices among neighboring farms in the LARV, fluctuating diverted flows to canals, significant discharge from ungaged tributaries during high rainfall events, and the wide range of return flow time lags from irrigation. Additional thought is given to the fact that tail-water runoff return flows were estimated based on field observations in 2004-2007, which were relatively dry years compared to 1999-2001. This may mean that tail-water runoff is under-predicted, and could interfere with return flow estimations and simulated values of recharge to the water table.

The purpose of this section is to provide a summary of the methodology and data applied to create the MODFLOW-UZF application for the LARV, and to justify its use in the study outlined in this thesis. It is known with certainty that, like all other models, the MODFLOW-UZF model is not perfect and contains a certain amount of error. However, Morway et al. (2013) show that the model is reasonably accurate due to its basis on a plethora of data and studies, and through a rigorous calibration and testing process. Such considerations have justified the acceptance of the calibrated MODFLOW-UZF numerical model for use in the study outlined by this thesis.

2.3. Previous studies evaluating the Glover-Balmer solution

2.3.1. Field studies evaluating the Glover-Balmer solution

During an eight day comprehensive aquifer test in central Kansas, Sophocleous et al. (1988) found that pumping 64 meters from the Arkansas River caused depletions in the river. When drawdown behavior did not resemble that of normal alluvium, the authors postulated that additional stream network components and a semi-confined, perched water table caused by a clay layer were also contributing to aquifer recharge. The authors compared results with the prediction of stream depletion from the Glover-Balmer (1954) analytical model and found that the analytical model over-predicted depletions considerably. The work by Sophocleous et al. (1988) was the first notable example of potential significant errors in using the Glover-Balmer solution in a real-world setting. This was followed by studies by Sophocleous (1995; 2005) and others in which potential errors caused by assumptions in the Glover-Balmer solution were explored in more detail. Nyholm et al. (2002) analyzed data from an aquifer test and created a calibrated MODFLOWP (Hill, 1992) numerical model for an area of about 3.23 km^2. The pumping well was located at a distance of about 60 m from the stream. They compared results to an analytical solution developed by Hunt (1999), which shares many of the same assumptions as the Glover-Balmer solution but differs in that it assumes small stream penetration, a linear relationship between the streambed outflow and the piezometric head change through the clogging layer, and a small stream areal cross section. Nyholm et al. (2002) found that Hunt's solution significantly overestimated stream depletion compared to the numerical model. Although Nyholm et al. (2002) note that their numerical model contains biases due potentially to the model's representation of release from storage or the hydrology of the riparian zone, it becomes clear upon review of more studies the trend of analytical solutions significantly overestimating stream depletion.

2.3.2. Evaluation of the Glover-Balmer solution by comparison to numerical models

Sophocleous et al. (1995) evaluated the significance of several of the major assumptions of the Glover-Balmer solution by comparison to a three-dimensional MODFLOW numerical model for a hypothetical aquifer. This study is referenced frequently in other investigations considering the Glover-Balmer solution. A relatively simple and hypothetical MODFLOW model was created to serve as a realm in which to compare the Glover-Balmer solution to a more sophisticated numerical model. The goal was to create a simple scenario of one pumping well and one stream in MODFLOW, and make modifications to the model to create different scenarios. In making modifications to the MODFLOW model, Sophocleous et al. (1995) were able to isolate the hydraulic parameters pertaining to many of the major assumptions made by the Glover-Balmer solution. For example, the assumption of a fully penetrating stream is evaluated by creating the MODFLOW model with a partially-penetrating stream while all other parameters remain consistent with the assumptions of the Glover-Balmer solution. In determining stream depletion following the insertion of a pumping well in the MODFLOW model, the same pumping rate and aquifer parameters can be provided to the Glover-Balmer solution to determine the difference between stream depletion estimates from both methods.

Sophocleous et al. (1995) noted that the largest discrepancies in stream depletion estimates between the MODFLOW numerical model and Glover-Balmer solution arise with the consideration of streambed clogging, partial stream penetration, and aquifer heterogeneity, which can cause errors of 58 – 71 %, 10 – 61%, and 7 – 38%, respectively. Inclusions of layered and transverse aquifer heterogeneity were also noted to cause significant errors in some cases. Parameters causing relatively small discrepancies include variation of stream stage, hydraulic conductivity (K), and S. In all cases except for that of transverse heterogeneity, it was found that discrepancies resulted in an overestimation of stream depletion by the Glover-Balmer solution. This result is consistent with all previously mentioned studies comparing the Glover-Balmer solution to more sophisticated analytical solutions. The significance of the study by Sophocleous et al. (1995) is in that the full capabilities of a finite-difference numerical model were applied to determine the sensitivity of most assumptions made by the Glover-Balmer solution. As in other studies, the assumptions of instantaneous release from the aquifer, that the aquifer receives no recharge, that the water table is initially horizontal, and that stream temperature is constant and equal to that of the aquifer are not directly considered. These assumptions probably create relatively small errors compared to the other assumptions.

Although the study by Sophocleous et al. (1995) is enlightening in determining the efficacy of the Glover-Balmer solution, it does not utilize a numerical model calibrated to data from a real world system, nor does it consider pumping wells at distance from the stream commonly seen in practice (greater than 100 m). Similarly, a comparison by Spalding and Khaleel (1991) in which the Theis (1941) analytical solution (which the authors note has the same assumptions as that of the Glover-Balmer solution) is compared to a hypothetical two-dimensional AQUIFEM model also showed that the assumptions of full aquifer penetration and perfect streambed conductance between the stream and aquifer can lead to significant errors. AQUIFEM is two-dimensional, transient numerical groundwater software. Spalding and Khaleel (1991) were not able to evaluate the assumptions of the Theis (1941) solution quite as extensively as Sophocleous et al. (1995), but provided a first attempt at comparing an analytical model to a numerical model. Again, the significant errors noted were in the form of overestimation of stream depletion by the Theis (1941) solution.

Miller et al. (2007) modified the Jenkins (1968) SDF to include boundary effects, and compared these results to a calibrated MODFLOW (Harbaugh et al., 2000) application for the Tamarack Ranch State Wildlife Area (TRSWA) near the South Platte River in northern Colorado. Miller et al. (2007) note that their modified SDF method performed well in comparison to the numerical model, and suggested it as a viable alternative to a numerical model. Miller et al. (2007) created response curves for several bounded, ideal aquifers using the the Glover-Balmer solution with an image well pattern. Miller et al. (2007) also apply a scheme in which imaginary wells are imposed to modify the Glover-Balmer solution to account for an aquifer boundary (Ferris et al., 1962), and can improve the Glover-Balmer solution by negating the assumption of a semi-infinite aquifer. For this reason the image well approach is applied in the study described in this thesis, and is illustrated in Figure 2.3. The distance to the stream, *a*, and the distance to the no-flow boundary, *b*, are applied to model the theoretical drawdown created by a no-flow aquifer boundary. The image well scheme extends *ad infinitum* or until an additional series makes a negligible impact on calculated stream depletion. The image well scheme requires the imposition of the principal of superposition (Franke et al., 1987) to account for the cumulative effects of a series of imaginary wells. The scheme attempts to model more closely the USR by imposing a model of the aquifer edge, which can be seen as a no-flow boundary.

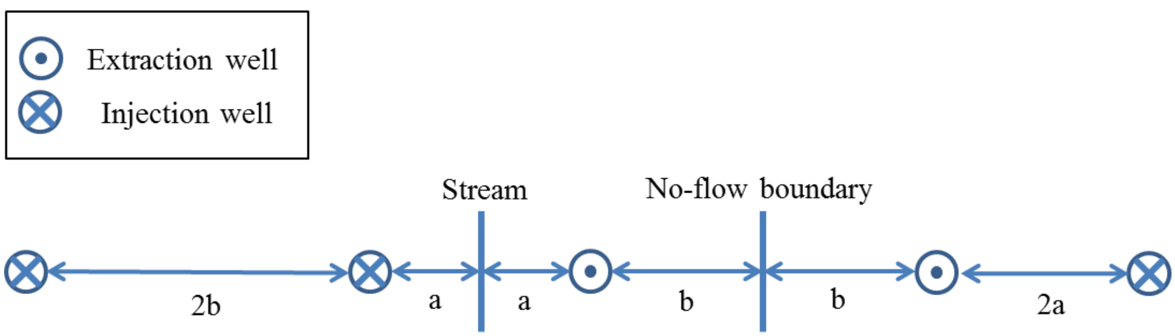


Figure 2.3. Image well scheme applied to the Glover-Balmer solution to account for a no-flow boundary.

Miller et al. (2007) verified using MODFLOW the response curves (a ratio of the total volume depleted from the stream divided by the total volume pumped versus time) from the Glover-Balmer solution. This metric is quite similar to the one applied in this thesis. The authors note that at distances relatively close to the stream, response curves from the Glover-Balmer solution including image wells were relatively close to those from the MODFLOW model. However, as the well position is moved further from the river and closer to the boundary, the response curves from the Glover-Balmer solution do not match those from MODFLOW as well.

Miller et al. (2007) then modify SDF values obtained from Jenkins (1968b), include image wells to account for an aquifer boundary, and compare them to the MODFLOW model. It was found that if the well was located at a point where $a / (a + b) < 0.47$ (where a and b are defined in Fig. 2.3), then the boundary has a negligible effect when t / SDF ≤ 1. However, they also note that the impermeable boundary can affect stream depletion at times greater than the SDF, even if pumping has ceased before the SDF time. Miller et al. (2007) go on to note that the timing and volume of river augmentation and depletion from both recharge and pumping operations usually are performed using the Glover-Balmer or SDF methods. The authors describe efforts modeling two hypothetical recharge ponds to assess the ability of the SDF method in predicting stream accretion. It was noted that the SDF method does well in predicting accretion when the wells are closer to the stream than they are to the impermeable boundary, and that image wells are ideal in creating a good response for wells closer to the impermeable boundary. The timespans used in modeling the recharge ponds close and far from the stream are 60 days and 200 days, respectively. These durations are not as long as those seen in larger alluvial valleys like the LARV, where pumping wells may exist at a distance of multiple kilometers from the stream and can cause depletions over the time spans of many years.

2.3.3. Summary of findings from previous studies evaluating the Glover-Balmer solution

The Glover-Balmer solution has been compared to several analytical solutions that address additional components such as limited stream penetration, a semi-conducting aquifer, and limited lateral extent. These studies have found that limited stream penetration and a streambed with limited conductance can significantly alter stream depletion estimates when compared to solutions that do not incorporate such hydrologic components (Zlotnik and Huang, 1999; Butler et al., 2001). Field work supporting the significance of stream-aquifer conductance and limited stream penetration was shown by Moore and Jenkins in 1966, who showed that groundwater pumping had caused the water table elevation to lower below that of the streambed, breaking hydraulic connection with the aquifer (as shown in Figure 2.4). Once hydraulic connection is broken, an unsaturated zone develops below the stream and infiltration estimates become more difficult to quantify. Moore and Jenkins attribute the principal control in this scenario to be the least-conductive layer in the streambed.

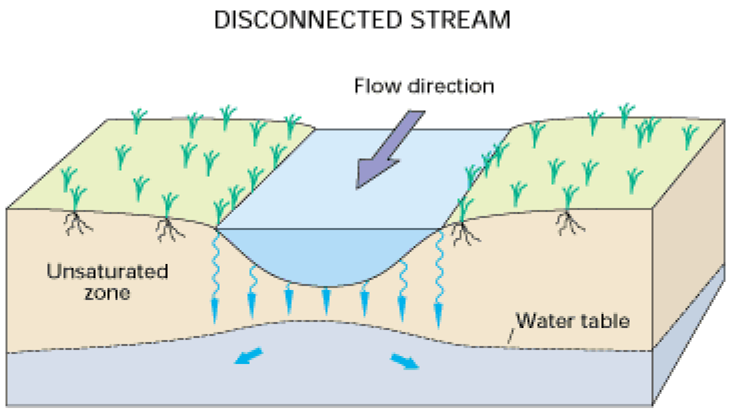


Figure 2.4. A pictorial representation of a stream that has lost connection with the water table. (http://pubs.usgs.gov/circ/circ1186/html/gw_effect.html, accessed 20 June 2014)

The MODFLOW-UZF model is able to account for stream and canal disconnections from the saturated zone as it simulates the study period described in this thesis. The water table in some areas may be sufficiently high such that good conductance with the stream is possible, while in others the water table could be lower than the river bed, creating an unsaturated zone and breaking connection. As is true of many rivers, parts of the Arkansas River can be receiving accretion from the groundwater aquifer while other parts of the river are discharging water to the aquifer through streambed leakage.

Many of the studies discussed previously in this chapter considered streambed clogging while comparing the Glover-Balmer solution to a numerical model solution (Spalding and

Khaleel, 1991; Sophocleous et al., 1995; Nyholm et al., 2002) or to newer analytical models (Zlotnik and Huang, 1999; Butler et al., 2001), and each noted its importance. Consideration to low streambed conductance within the study described by this thesis is accounted for somewhat differently. During construction of the MODFLOW-UZF model application for the LARV, the hydraulic conductivity of the streambed material was assumed to be the same as that of the adjacent alluvium. This came from observation and experiences noting that the river bed materials appeared to be very sandy and conductive. However, since the model is calibrated to physical data from the LARV, during the automated calibration with UCODE in which the parameters of hydraulic conductivity and specific yield are adjusted, any effects of streambed clogging will be accounted for indirectly through adjustment of the two variables. As explained in detail in Chapter 3, during comparisons of the MODFLOW-UZF model and the Glover-Balmer solution, aquifer parameter values supplied to the Glover-Balmer solution are obtained from the values obtained by the calibration of the MODFLOW-UZF model. Therefore, because the MODFLOW-UZF model is indirectly accounting for streambed conductance through the automated calibration process, and aquifer parameters for the Glover-Balmer solution are supplied by the MODFLOW-UZF model, the Glover-Balmer solution is accounting for streambed conductance through its use of the MODFLOW-UZF aquifer parameters. Through conversations with engineers and state officials, it is known that such detailed parameter data are not normally available in applying the Glover-Balmer solution, making the comparisons outlined in this thesis ideal. Conversations revealed that available data often include lithological data from well driller's logs, or parameter data from state or federal entities (e.g. DWR, USGS)

It was mentioned previously in Chapter 2 that no studies to date have made a comparison of the Glover-Balmer solution to a numerical model or more complex analytical model for pumping wells at distances from a major stream greater than around 100 m. Most wells within the LARV reside at distances on the order of a few hundred meters up to several kilometers from the main stem of the Arkansas River. This allows for the observation of long-term effects on the stream network, along with regional changes in the groundwater flow regime, and compares the MODFLOW-UZF model to the Glover-Balmer solution at distances not considered by previous studies.

Another unique aspect of this study is its use of a regional-scale, calibrated finite-difference numerical model as the basis for evaluation. Although there are other examples of studies comparing the Glover-Balmer solution to numerical models, the modeled systems are either hypothetical or are of much smaller areal extent. The MODFLOW-UZF model application for the LARV allows comparisons to the Glover-Balmer solution within an aquifer with considerable parameter variability (e.g. hydraulic conductivity and specific yield), a relatively wide range of hydrologic conditions, and significant physical complexity. This allows one to compare the Glover-Balmer solution to a numerical model that more effectively considers many of the multi-faceted features of a regional widely-irrigated alluvial valley.

METHODOLOGY

This chapter describes the methods used to compare the Glover-Balmer solution to the MODFLOW-UZF numerical model calibrated for the LARV. Modifications made to the MODFLOW-UZF model to simulate lease-fallowing, water extraction, and water addition scenarios are explained. Each comparison of the MODFLOW-UZF model and the Glover-Balmer solution is called a "scenario". A scenario is defined as an instance of the MODFLOW-UZF model in which a single field or model grid cell receives a water stress (removal by fallowing, extraction, or addition) as an alteration to the baseline condition (unmodified instance of the MODFLOW-UZF model) and is modeled using both the MODFLOW-UZF model and the Glover-Balmer method. Scenarios are set up for simulation by the MODFLOW-UZF numerical model in a manner comparable (utilizing data and inputs that are as similar as possible) to their analysis with the Glover-Balmer solution. A description of how parameters used in the MODFLOW-UZF model are used as inputs to the Glover-Balmer solution (Q, x, T, S_y) is presented.

3.1. Study Area

The LARV resides in the semi-arid western United States in southeastern Colorado, as depicted in Figure 1.2. The Arkansas River begins in the Rocky Mountains in central Colorado, and flows east through the plains of eastern Colorado before exiting the state into Kansas. The Arkansas River has supported agriculture in the LARV since the mid-19th century (Abbott, 1985), and current irrigation efforts are supported by 25 main canals, which are composed of a total length of more than 1,000 miles, and by about 2,400 wells that extract water from the alluvium (Gates et al., 2012).

Although the extensive irrigation system has supported a highly productive agricultural region, problems have arisen as a result of excess irrigation, canal seepage, and inadequate drainage (Gates et al., 2006). The most significant problems include waterlogging and salinized arable land, which accompany higher levels of other dissolved elements, like selenium, which can rise to toxic levels. These conditions have resulted in degraded soil conditions with accompanying decreased crop yields and diminished water quality in the aquifer and streams. The USR is the focus of this study, and significant efforts of extensive data collection began there in 1999 by Colorado State University (CSU) researchers. Data collection and monitoring have included ground water monitoring, analysis of river and tributary flows, analysis of flows diverted to irrigation canals, surface water quality measurements, intensive soil salinity monitoring, topographic and hydrographic surveying using differential global positioning systems (GPS), drilling boreholes to explore lithology and bedrock, measurement of soil and aquifer properties, measurement of seepage from irrigation canals, measurement of irrigation applications and runoff, measurements of crop yield, and other related activities (Gates et al., 2002; Burkhalter, 2005; Burkhalter and Gates, 2005; Jaramillo et al., 2005). More details regarding data collection and the results of various studies can be found in Gates et al. (2006), Gates et al. (2009), and Gates et al. (2012).

The recognition of the interconnectedness of groundwater and surface water systems in the LARV has led to concerns regarding the effect of irrigation pumping wells on the Arkansas River. The major motivation behind the Kansas v. Colorado Supreme Court case (US Supreme

Court, 1995) was the concern of significant depletion to the Arkansas River due to groundwater pumping. Cases such as this, coupled with the popular use of the Glover-Balmer solution for estimating aquifer-stream interactions in Colorado (described in Chapter 2), creates a significant need to consider the suitability of the Glover-Balmer solution in practice.

3.2. Comparisons of the MODFLOW-UZF model application for the LARV and the Glover-Balmer solution

3.2.1. Comparisons of the MODFLOW-UZF model and Glover-Balmer solution for lease-fallowing scenarios

The first scenario type evaluated is that of lease-fallowing. These scenarios are established to mimic a typical fallowing scenario in which all irrigation water is removed from a field. Removal of irrigation is quite different than well pumping; pumping involves removal of subsurface water from the saturated zone while irrigation water is "subtracted" by ceasing application to the ground surface. However, by removing water from a field, recharge to groundwater often is reduced and the water table is lowered. In the case of a water rights transaction, when irrigation water is transferred from a field to another use (lease-fallowing), a comparison must be made between what is likely to happen once the water is removed in comparison to baseline conditions before the water is removed. When irrigation water is removed, two outcomes are possible: (1) less groundwater is accreted to the stream system because less water is infiltrating into the subsurface, or (2) additional water is depleted from the stream network, caused by a reversal in the hydraulic gradient due to the removal of irrigation. In reality, because the stream network can be gaining and losing water concurrently at different locations, a combination of both is possible. However, this situation generally is simplified for legal and practical applications, so that the reduction of groundwater recharge due to irrigation removed from fallowed fields is assumed equivalent to an instance of groundwater pumping. Engineers and state officials familiar with water rights transactions in Colorado have stated that the Glover-Balmer solution can be used in the manner aforementioned to quantify stream depletion due to the removal of irrigation water from a field. This creates an impetus to compare the impact of such fallowing scenarios predicted by the Glover-Balmer method with predictions by the calibrated MODFLOW-UZF model.

The fallowing scenarios presented include consecutive three-year periods and one-year periods. The three-year period selected for fallowing is the first three years of the simulation period. For the one-year fallowing scenarios, each field was fallowed for three separate instances in which a different year within the simulation period was selected for fallowing. Such scenarios allow exploration of differences that arise due to different hydrologic conditions. Preprocessing computer code was created for the MODFLOW-UZF model to remove all irrigation water from the field of interest. This means removing all irrigation application from every model grid cell associated with the fallowed field. When a field is selected to receive irrigation in the MODFLOW-UZF model, water is apportioned to each grid cell associated with the field in proportion to the area within the grid cell that overlies the field. As a simplified example, if an irrigated field receives 1 unit of water and the field is covered by two grid cells with 40% of the area of Grid Cell 1 and 60% of Grid Cell 2 overlying the field, then Grid Cell 1 receives 0.4 units of water while Grid Cell 2 receives 0.6 units. Therefore, when irrigation water is removed from a field, it can mean that the total volume allotted to a cell is removed if it completely covers the field (or partially covers the field and vacant land), or a portion of the total is removed if the cell overlays multiple fields.

In order to mimic actual lease-fallowing conditions (Bidlake, 2002), ground cover for the specified field is changed to grass during the year(s) of fallowing. All variables associated with the crop type also change, including ET and rooting depth. The total volume of water removed during each irrigation event is recorded in addition to the date of occurrence in the simulation period (different fields may be irrigated at different times). The total volume of each irrigation event is then treated as a "pumping rate" in the Glover-Balmer solution. The Glover-Balmer solution traditionally estimates stream depletion/accretion for a single pumping time step. However, the principal of superposition can be applied to model pumping rates that are variable and not consecutive (like the removed irrigation applications in lease-fallowing), and long-term depletion that occurs as a result of the hydraulic gradient driving groundwater flow towards the pumped well after the pumping period ends (Franke et al., 1987). In summary, by applying superposition, varying irrigation volumes removed at varying timesteps can be utilized in the Glover-Balmer solution to model stream depletion. These methods can be reviewed in detail in the publication by Barlow and Leake (2012).

To adequately encompass changes from the baseline scenario due to stress events, the MODFLOW-UZF simulations are extended to a 32 year period by repeating the 10.5-yr 1999-2009 simulation three times, with the end of each 10.5-year simulation used as the initial conditions for the next 10.5-year simulation. To determine the effects from the stress, MODFLOW-UZF outputs for the stressed scenario are compared with MODFLOW-UZF outputs from the baseline (unstressed) scenario, with results subtracted from the baseline scenario to estimate the impacts of the water fallowing, extraction, or addition (extraction and addition scenarios are explained later in this chapter) on the hydrologic system. These outputs include depletion/accretion to the river main stem, individual canal seepage, tributary depletion or accretion, changes in water table depth, groundwater storage, unsaturated zone ET, and upflux to ET from the saturated zone. Computed infiltration and surface runoff components also are examined. In using the Glover-Blamer model, only stream depletion/accretion is estimated.

In order to create commensurable comparisons aquifer parameters values calibrated with the MODFLOW-UZF model are used in the Glover-Balmer model. It was assumed that the aquifer specific elastic storage is relatively small (Theis, 1935), so that storativity was assumed equal to specific yield (S_y), which is the value used for the analyses. As is common in real-world applications of the Glover-Balmer solution, the flow path to the Arkansas River was chosen as the minimum-distance straight line from the field to the river. The aquifer parameters of the numerical model cells intersected by the straight line were selected for use in estimating values of T and S_y to be used in the Glover-Balmer solution. Due to the fluctuating water table elevation during the simulation, the T value (computed as the layer-averaged product of hydraulic conductivity and saturated aquifer thickness) in each MODFLOW-UZF cell varies over the weeks of the simulation. In order to obtain a single value for each cell, an arithmetic average over the simulation period is taken over all the grid cells along the flow path between the field and the river. A single T value and S_y value were then obtained for use in the Glover-Balmer solution by taking a harmonic average of the values in the cells along the flow path (Freeze and Cherry, 1979; Aral and Taylor, 2011). Figure 3.1 shows examples of the straight-line selection of models cells for a few example fields.

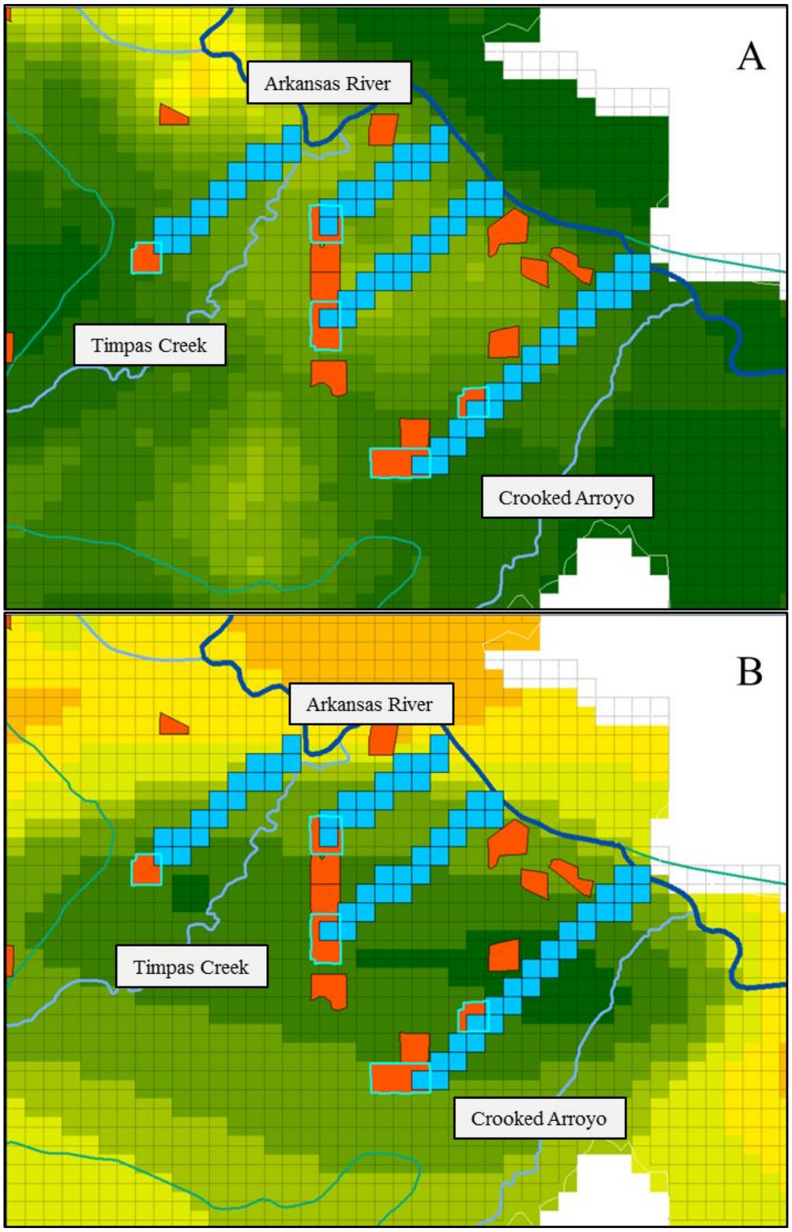


Figure 3.1. Examples of the selection of model cells in a straight-line (blue cells) for several example fields (shown in orange), with minimum distance from the Arkansas River for time- and depth-averaged (A) T values, and (B) S_y values.

As discussed in Chapter 2, this scheme allows for the use of parameters that represent the natural system more closely than would be expected in many applications of the Glover-Balmer solution. This is because the Glover-Balmer solution is receiving aquifer parameter values that are averaged over numerous grid cells, and each grid cell value is an estimate resulting from calibration against field data. This is in contrast to the sparse data sets typically available in most regions in which the Glover-Balmer solution is applied. Most data sets are more spread out than the values estimated using the MODFLOW-UZF model.

The inclusion of an aquifer boundary partially negates the assumption of a semi-infinite aquifer imposed by the traditional Glover-Balmer solution. The boundary applied creates a second, perfectly straight boundary parallel to the stream. For this study, the aquifer boundary is considered to be a no-flow boundary and is defined by the furthest extent of arable land in the LARV, which coincides with the MODFLOW-UZF model boundaries. The USGS program STRMDEPL08 (Reeves, 2008) was used to perform the aforementioned procedures in applying the Glover-Balmer solution on a weekly time step (to match the MODFLOW-UZF model), accounting for a variable pumping rate and long-term effects using superposition, and employing image wells to account for a constant head or no-flow boundary. The assumptions and methods utilized by STRMDEPL08 to model long term depletion/accretion due to aquifer stress events are outlined in detail in a USGS publication by Barlow and Leake (2012). Figure 28 in the report by Barlow and Leake (2012) shows the graphical representation of the approach employed by STRMDEPL08 and thee response as the stream network.

3.2.2. Comparisons of the MODFLOW-UZF model and Glover-Balmer solution for water extraction/addition scenarios

Following exploration of lease-fallowing scenarios more standardized scenarios, which would be more comparable to one another, were desired. In a lease-fallowing program, agricultural producers remove irrigation water from selected fields and temporarily lease those water quantities to municipalities or industries. Since the lease-fallowing scenarios described in this study involve fields within a physically-based model of the LARV, field size, volume and timing of removed irrigation water, crop type, and proximity to canals and tributaries are considerably variable between the scenarios. With this is mind, new scenario types were defined which make individual scenarios more comparable. For reasons explained in Chapter 2, it was desired to explore stress events as water extraction and injection from the saturated zone. It also was decided that stressing a single grid cell would make comparisons between scenarios more uniform since fields can vary significantly in size while grid cells do not. Furthermore, the size of the stress event can be held constant, in contrast to the removal of irrigation applications which vary significantly in amount and timing over the simulation period. Additionally, the effects of a single stress event can be isolated if the stress is applied during a single set of consecutive timesteps. Specifically, in this study stresses in the form of water extraction or addition to the saturated zone were applied evenly over four time steps.

Applying stresses to the saturated zone, as opposed to the ground surface, more closely resembles real pumping or injection wells (as compared to the lease-fallowing scenarios and are thereby more amenable to the Glover-Balmer solution. Each stress was applied as a 25 acre-feet (about 30,800 m^3) extraction/addition, spread evenly over four consecutive model time steps (weeks). A value of 25 acre-feet was selected as a sufficiently large volume to induce significant effects in the MODFLOW-UZF model. Units of acre-feet were used because results were presented to an audience most familiar with U.S. customary units. Weeks 61-64 are selected to receive the stress event in each scenario. In the model simulation period, this corresponds to the month of June 1999. In comparison to other simulation years, 1999 was a relatively wet year (especially compared to 2002 and 2003, in which an intense drought occurred). The hydrologic conditions did not serve as a guide in selection of the extraction/addition timing, but were chosen to be near the beginning of simulation period to allow for a large simulated response period in the MODFLOW-UZF model following the stress event. Stresses are created in the MODFLOW-UZF model by modifying the WEL file, which lists the pumping wells and pumping rates for each model timestep. The WEL file is also used for water addition scenarios, where a positive value is used to model water addition (or an injection well). This stress is in addition to irrigation and precipitation events that occur within the model; all other calibrated parameters and data remain unchanged. Figure 3.2 shows a flow chart describing the scenarios, the inputs and outputs for the MODFLOW-UZF and Glover-Balmer models, and a map of the location of all extraction/addition scenarios. The Glover-Balmer solution is identical to that employed in the lease-fallowing scenarios, including the use of the STREAMDEPL08 software to apply a no-flow boundary using image wells and to simulate long term effects using superposition.

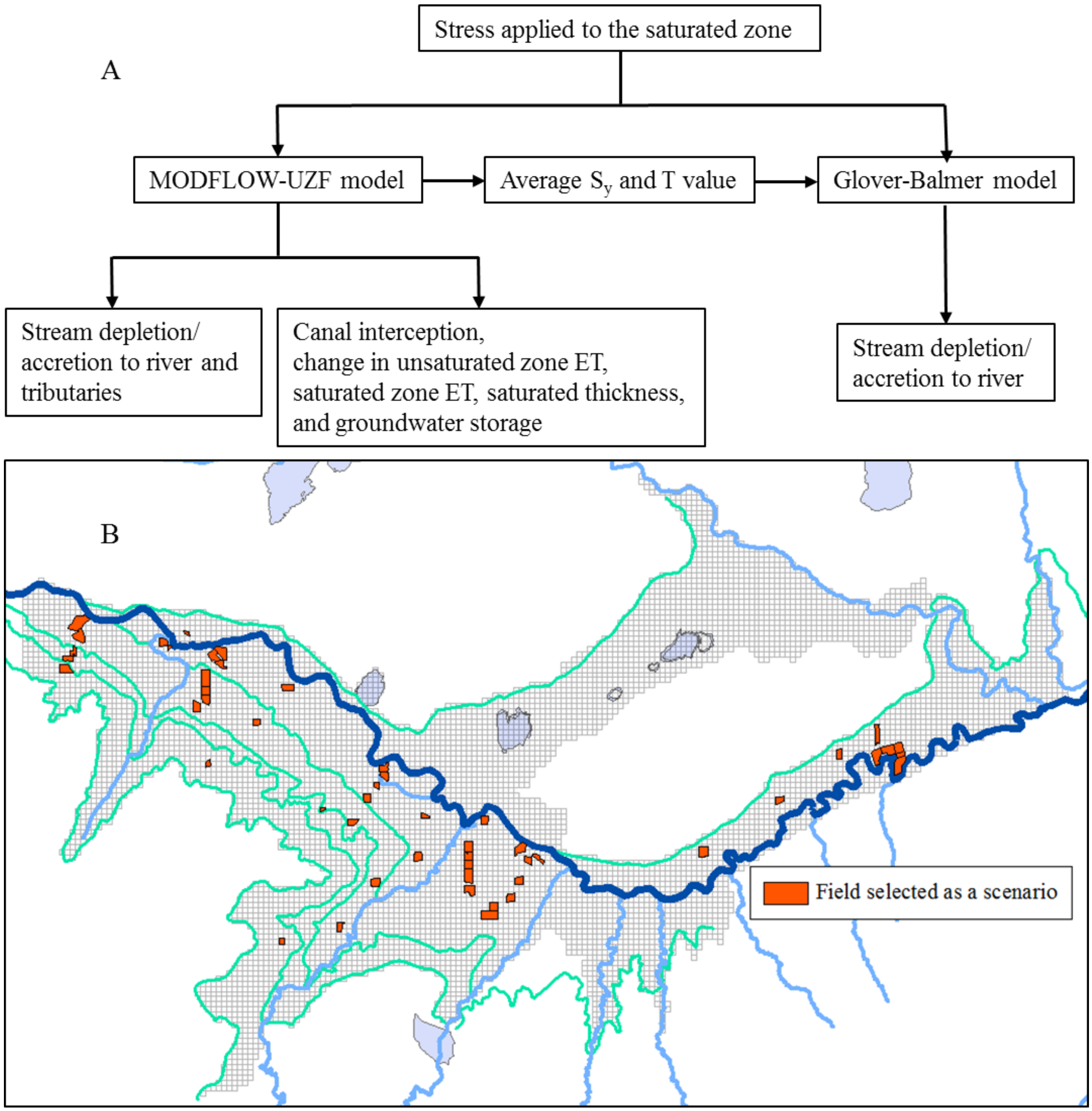


Figure 3.2. (A) Flow chart of the general structure of extraction/addition scenarios used for the evaluation of the Glover-Balmer solution by comparison to a calibrated MODFLOW-UZF numerical model, and (B) the fields selected as comparison scenarios within the LARV.

To obtain results that are representative of the complexity and variability of the LARV, an array of fields is selected to individually receive water stress as extraction or addition. Fields are chosen with various proximities to stream network components, lithology, crop type, irrigation pattern, and general hydrologic conditions. Crop types considered include onions, melons, alfalfa, corn, soybeans, and grass (pasture). Distance of selected grid cells from the Arkansas River ranged from 250 m to nearly 6000 m, with the majority of locations residing within about 3000 m. Figure 3.2B depicts the locations of the 54 fields selected as scenarios. Both scenario types (extraction and addition) were applied to each selected field. Forty-eight water-addition scenarios are presented because in six cases the saturated zone filled completely, allowing little or no infiltration from irrigation or precipitation following the stress event. Therefore, water applications for 2-4 weeks following the water addition stress event were generated as runoff by the MODFLOW-UZF model. Such scenarios were not representative or conducive to determining impacts to the stream network, and were not included in the results. STRMDEPL08 and the MODFLOW-UZF model produce estimates of depletion/accretion to the stream network at weekly intervals. Due to the existence of a shallow water table in many parts of the LARV, changes in water table depth and aquifer saturated thickness were monitored in the analysis to account for potential changes in ET from the vadose zone and upflux to ET from the water table, which have been shown to be potentially significant (Niemann et al., 2011). The numerical model also was used to assess changes in canal interception, infiltration, recharge to the water table, and groundwater storage.

A third scenario type, a variation of the water addition scenario, is also presented. Initial water addition methodology involved stressing the system by pulsing water to a single grid cell at the ground surface. It was later realized that this methodology was not the same as the water extraction scenarios, where water was taken from within the saturated zone. Although the preferable methodology involves water addition to the saturated zone, some insight can still be gained from scenarios involving addition at the ground surface. The set of stressed grid cells are the same as those in scenarios involving addition and extraction to the saturated zone, highlighted in Figure 3.2B. Similar to the scenarios types presented previously, water is added evenly over a four week period. In some instances, when water is added to the ground surface in the MODFLOW-UZF model, the model may determine that only a portion of the added volume can infiltrate into the subsurface during a single time step with the remaining water is treated as runoff. This occurs if the application exceeds the infiltration rate assumed by the model. During simulation of several ground surface water addition scenarios in the MODFLOW-UZF model, a substantial portion of the 25 acre-feet pulse was unable to infiltrate the ground surface. In such cases, the stress volume was lowered to 20, 15, or 10 acre-feet. Although such reductions often allowed for complete infiltration of the stress volume, it created scenarios that were not as comparable to each other due to the altered stress volumes. In some instances, ground surface infiltration rates were dominated by irrigation or precipitation events already occurring within the model, and no additional stress volumes could infiltrate. Such cases were not included in considered results, but reduced volumes with an acceptable amount of infiltration (greater than 90%) were included. Due to the occasional limitations in infiltration, only 49 scenarios are presented here.

The method used to analyze stream depletion estimates from the Glover-Balmer solution is to plot the ratio $Q_{r,\,cumulative}/Q$, expressed as a percentage, versus time, called a unit response function (URF). Interactions with engineers and state officials in the LARV revealed that URFs are commonly used to display stream depletion in relation to the total water extraction/addition volume over time. Similar plots of URFs can be produced using the MODFLOW-UZF model predictions of stream depletion. URFs from both models can be plotted together to compare the overall predictions of stream depletion/accretion, an example of which is shown in Figure 3.3.

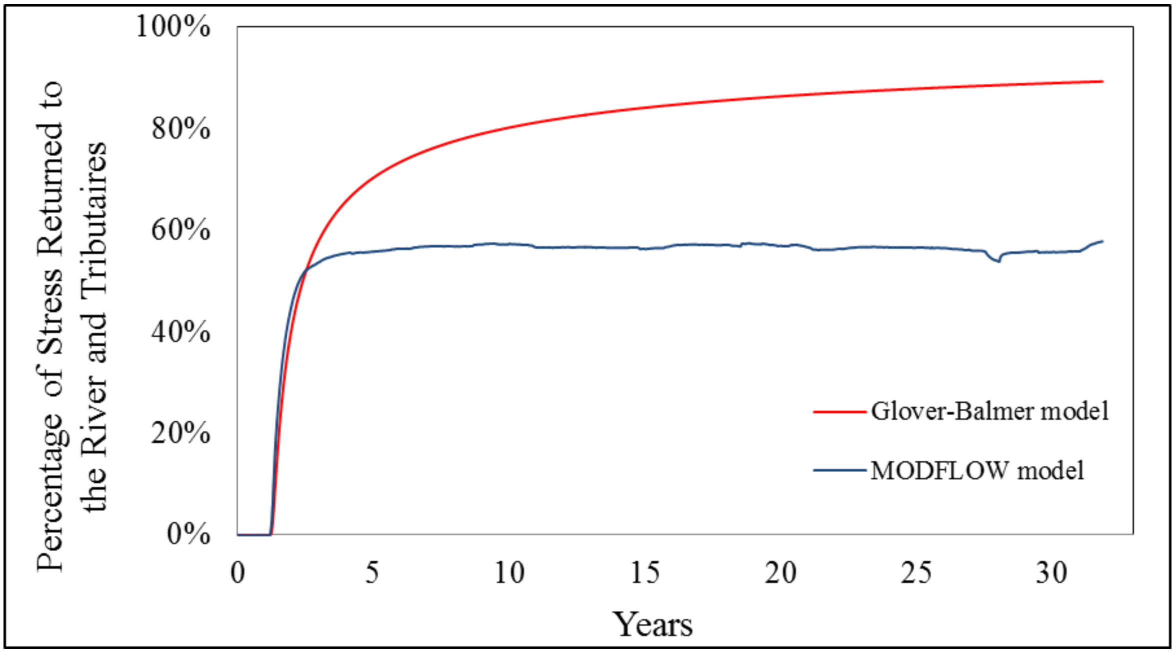


Figure 3.3. An example of URFs developed from the Glover-Balmer model and the MODFLOW-UZF model for a particular scenario.

For all extraction/addition scenarios, a ratio between the percentages of the stressed volume estimated as depletion/accretion to the stream network ($Q_{r,\ cumulative}$ / Q) using the MODFLOW-UZF model and that estimated using the Glover-Balmer model can be produced. This ratio, expressed as the MODFLOW-UZF model percentage divided by the Glover-Balmer model percentage, depicts how closely the simpler analytical model estimates are in relation to those of a more complex calibrated numerical model. If the two solutions predict the same depletion/accretion impact to the stream network, the ratio will equal 1. If the Glover-Balmer model predicts a higher depletion/accretion impact to the river than the MODFLOW-UZF model, the value will be less than 1.

RESULTS

Both general results and results for some special cases warranting consideration are presented for all four scenario types (lease-fallowing, water addition to the saturated zone, water addition to the ground surface, and water extraction from the saturated zone). Both instances in which stream accretion/depletion predictions from the Glover-Balmer solution and MODFLOW-UZF model match relatively closely, and cases in which they differ significantly are described. Additionally, overall trends are highlighted.

4.1. Results for lease-fallowing scenarios

Lease-fallowing scenarios were explored at the onset of the study. Therefore, the main focus of these scenarios is on comparison of stream depletion estimates and on the change in water table elevation due to fallowing as predicted by the MODFLOW-UZF model. Some consideration is given to changes in upflux to ET from the saturated zone, though this is not explored in as much detail as in the case of the extraction/addition scenarios. As the methodology continued to develop and new questions arose, more detailed results were obtained and analyzed for the water extraction/addition scenarios. Although results for lease-fallowing scenarios are not presented in the same detail as for the extraction/addition scenarios, they are included because they reveal useful insights into a water management practice that is used in the LARV.

4.1.1. Three-year lease-fallowing

An initial set of scenarios is presented in which an irrigated parcel was fallowed for three consecutive years beginning in 1999 (the first year of the simulation) in an attempt to explore the more extreme cases of lease-fallowing. Field 1 has an area of about 33.5 hectares (82 acres) and is located at a moderate straight-line distance from the Arkansas River of about 1500 meters, as shown in Figure 4.1. Irrigated fields in the LARV reside at straight-line distances from the Arkansas River of about 250 m up to over 10,000 m.

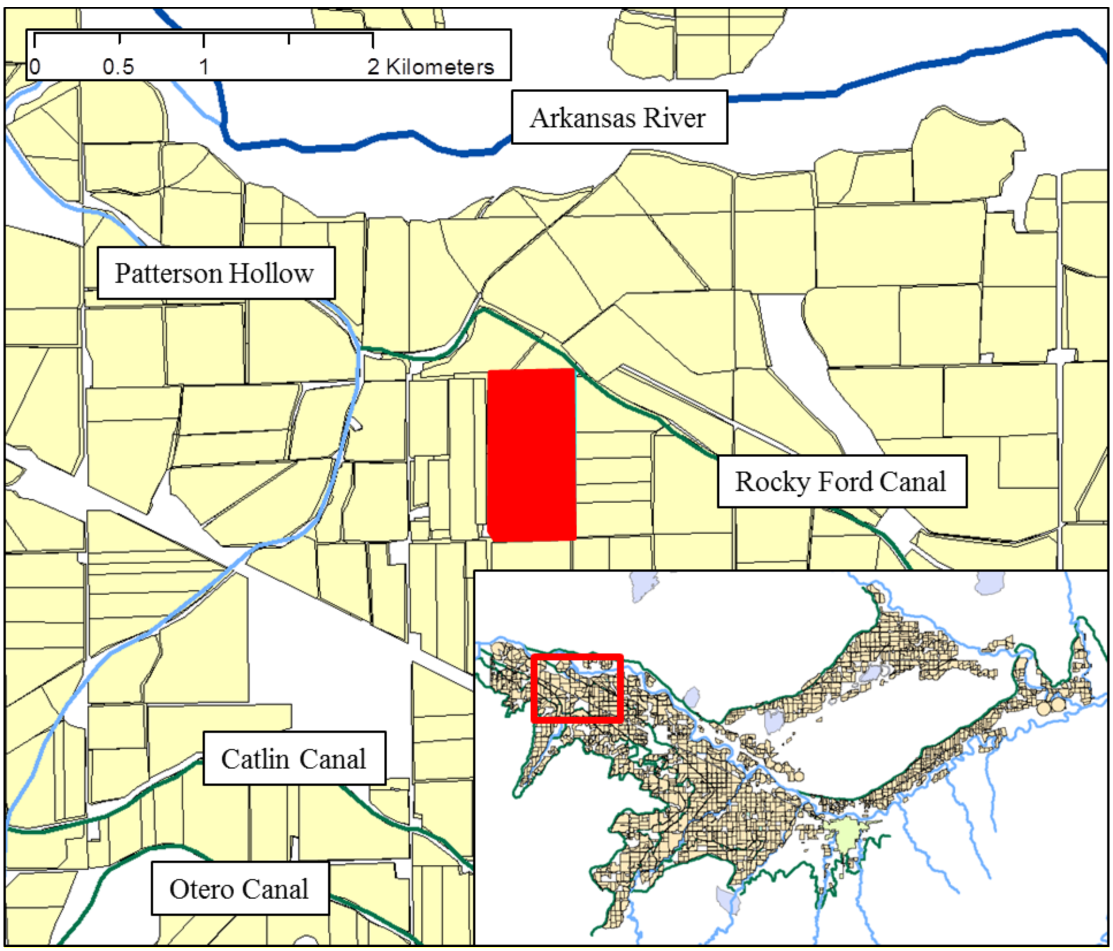


Figure 4.1. The location of Field 1 within the LARV.

Field 1 resides relatively close to Patterson Hollow, with the Rocky Ford Canal residing between it and the Arkansas River. Major results for Field 1 are shown in Figure 4.2. The time series plot shown in Figure 4.2A is limited to the first 10 years of simulation because the majority of stream depletion is estimated to occur during this period. The predictions of stream depletion from the MODFLOW-UZF model consider both the Arkansas River and its tributaries. The Glover-Balmer solution yields estimates only for the Arkansas River. The shape of both the MODFLOW-UZF and Glover-Balmer total depletion curves are relatively similar. However, the curve representing the Glover-Balmer solution depicts larger stream depletions at most timesteps, and continues to estimate significant depletions from years 4 to 6, where as the MODFLOW-UZF model predicts relatively little stream depletion after about 3.5 years. The total stream depletion volume predicted by each model, shown in Figure 4.2A, reveals that the Glover-Balmer solution predicts a stream depletion volume almost 700,000 m^3 larger than that predicted by the MODFLOW-UZF model. This discrepancy is relatively large when compared to other fallowing scenarios, and is equivalent to a depth of about 2 m on the fallowed field.

The cumulative stream depletion, expressed as a percentage of the total irrigation water removed (stress) during the fallowing period, is shown in Figure 4.2B. The Glover-Balmer solution begins overestimating total stream depletion in comparison to the MODFLOW-UZF model in about the second year of simulation and continues for the entire simulation period. Differences in stream depletion predictions occur in part because the MODFLOW-UZF model is accounting for additional hydrologic complexities such as ET, canal seepage, and groundwater storage change. As a simplified analytical solution, the Glover-Balmer solution can only attribute stresses to stream depletion, assuming that all water removed from the field will result in stream depletion eventually. If Figure 4.2B were extended indefinitely, the plot of the Glover-Balmer solution would attain a value of approximately 100%. This is not true of the MODFLOW-UZF model, where removed water will effect changes in ET, canal seepage, and groundwater storage change as well as return flow to the stream network.

Figure 4.2C shows the change in water table elevation predicted for each grid cell in a straight-line path from the fallowed field to the Arkansas River. Distances (shown in the legend) are measured from the Arkansas River to the center of each grid cell. Therefore, grid cells pertaining to the larger distances in Figure 4.2C are further from the river and closer to the fallowed field. The water table elevation change is calculated as a difference from the baseline (unchanged) condition using MODFLOW-UZF model results. Thus, negative values indicate a lowering of the water table elevation. As affirmed by Figure 4.2C and similar plots, cells further from the river (and closer to the fallowed field) experience much larger drops in water table elevation. As is true in the case of a classic cone of depression due to groundwater pumping, the water table lowers more drastically near the pumping site, and lowers less as distance from the pumping location increases. This is consistent with what is seen in the MODFLOW-UZF model. It can also be seen from Figure 4.2C that the change in water table elevation diminishes to zero between the third and fourth year of simulation. This means that the water table recovers a few months after the end of the fallowing period, an outcome that occurs frequently in scenarios explored by this study.

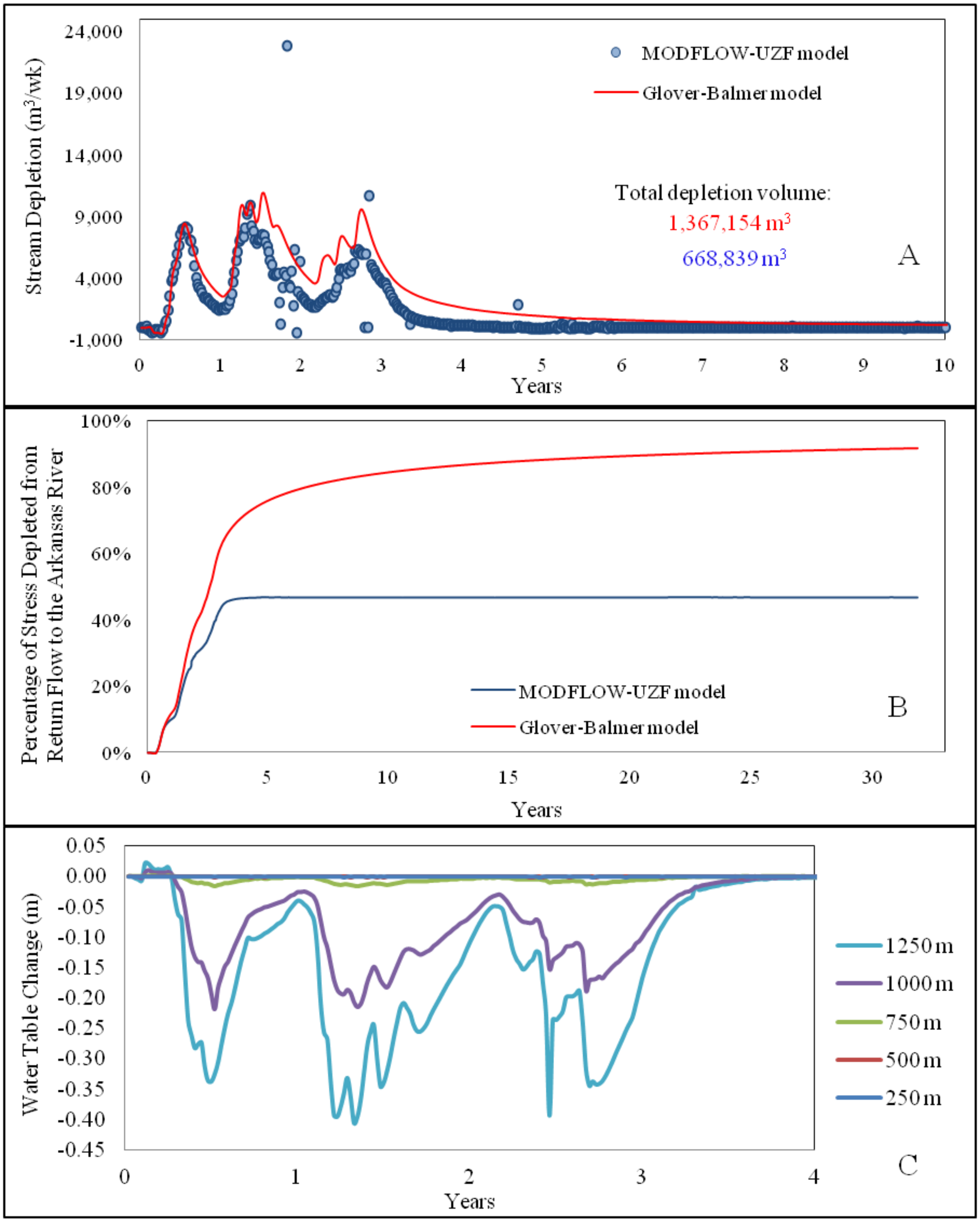


Figure 4.2. (A) The amount of stream depletion occurring at each timestep throughout the 32-year simulation period, as predicted by the Glover-Balmer solution and MODFLOW-UZF model, (B) the cumulative depletion expressed as a percentage of the total fallowed volume, and (C) the change in water table elevation for each cell in a straight-line path from the Arkansas River to the fallowed field.

Figure 4.3 compares predicted upflux rates to ET from the water table for the 32-year simulation period for Field 1 in both the fallowing and baseline MODFLOW-UZF scenarios. Considerably smaller upflux rates to ET in the fallowing scenario for the first three years of simulation results from the change in vegetation (from a cultivated crop to grass) and the drop in water table elevation due to the elimination of recharge from irrigation. As the water table lowers, less water is available to vegetation from the saturated zone. Additionally, the potential ET values for grass employed by the MODFLOW-UZF model are less than those of cultivated crops.

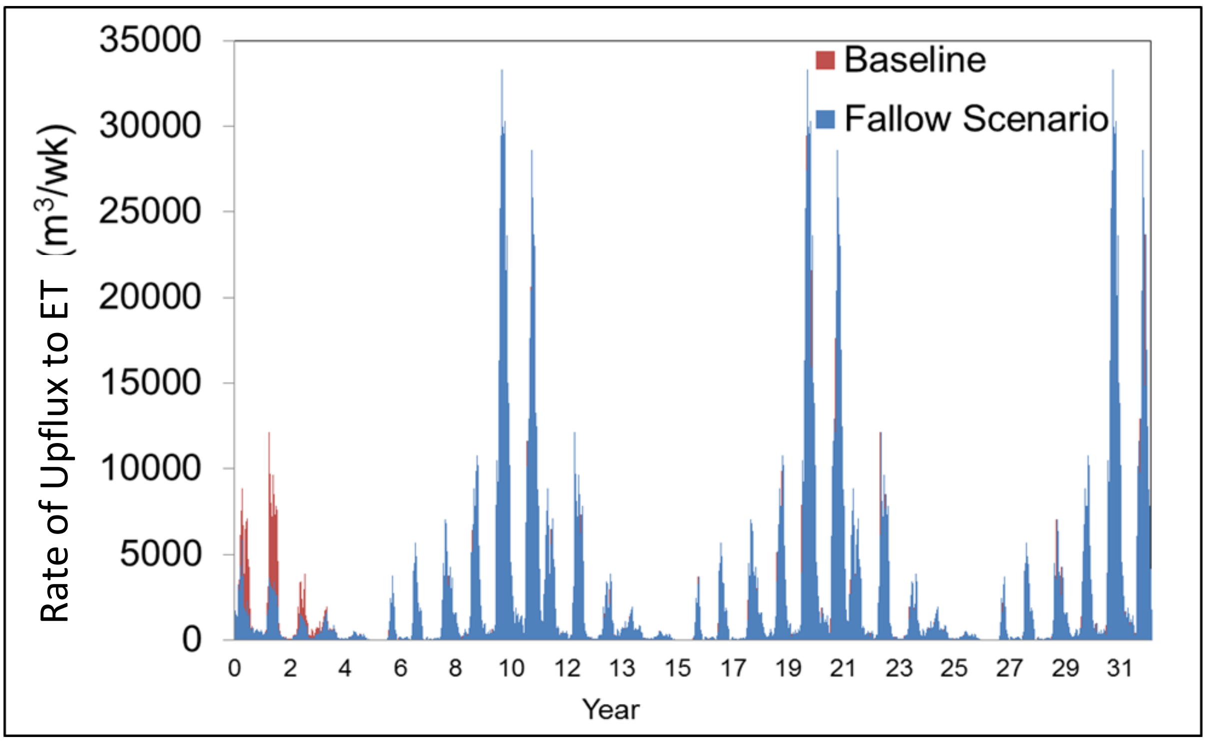


Figure 4.3. Predicted contribution to ET by upflux from the saturated zone for the baseline and fallowing MODFLOW-UZF scenarios.

Field 2 exemplifies a fallowing scenario at an increased at a straight-line distance of about 2,100 m from the Arkansas River, with an area of about 23.8 hectares (59 acres), as shown in

Figure 4.4. Field 2 resides between Timpas Creek and Crooked Arroyo, which are roughly parallel to each other and tributary to the Arkansas River.

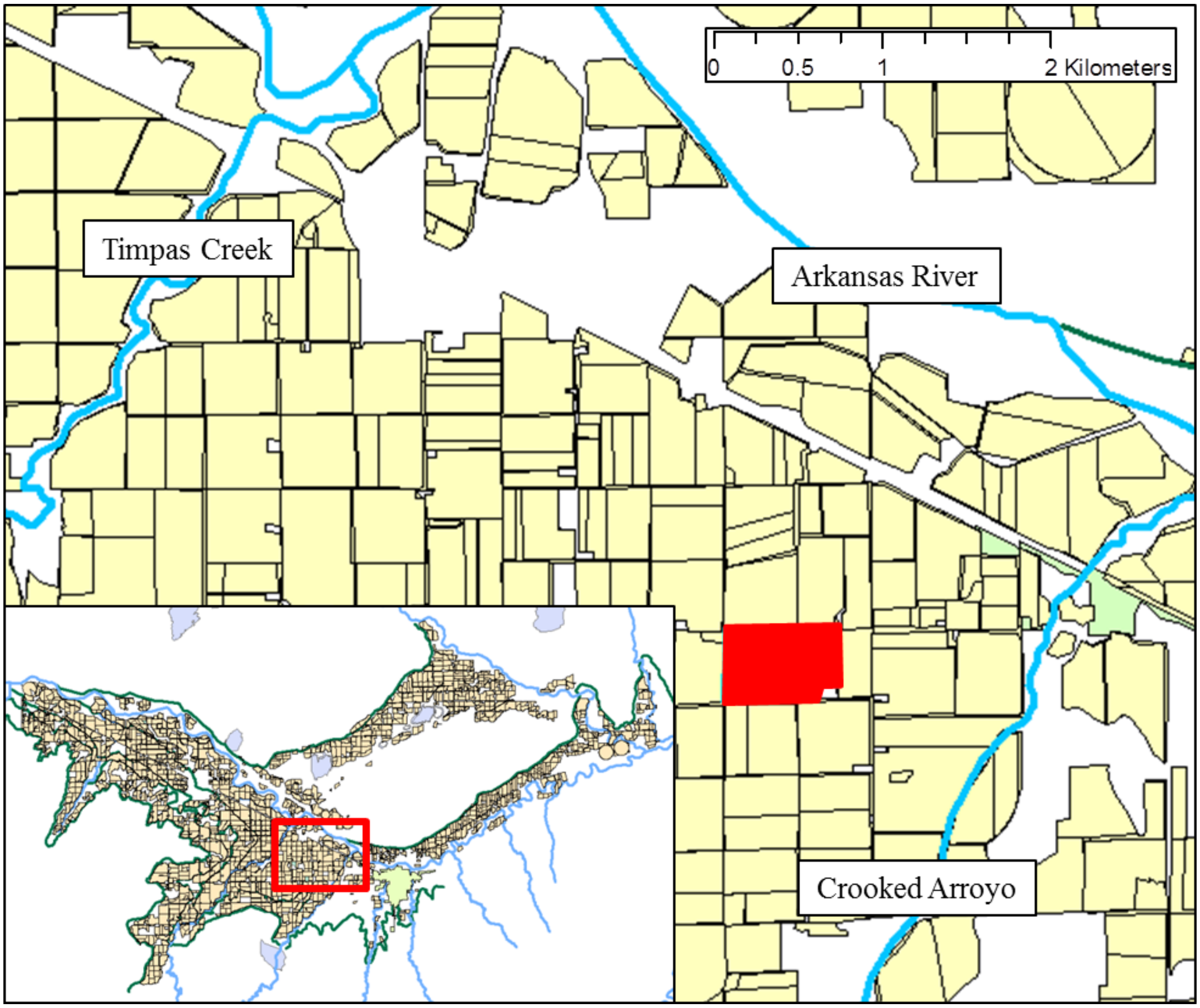


Figure 4.4. The location of Field 2 within the LARV.

Major results for Field 2, similar to those shown for Field 1, are shown in Figure 4.5. The time series plot sown in Figure 4.5A is limited to 15 years because predictions of stream depletion from the MODFLOW-UZF model and the Glover-Balmer solution largely diminish by this time. The peaks in both curves can be associated with the elimination of larger irrigation events at the height of each growing season. Three peaks are present since fallowing occurred for three years. The magnitudes of stream depletions are significantly lower than those computed for Field 1. This is because Field 2 was irrigated under baseline conditions with a lesser volume than Field 1 in the MODFLOW-UZF model. Although the shape of stream depletion curves from the MODFLOW-UZF model and the Glover-Balmer solution are relatively similar, the Glover-Balmer solution predicts the occurrence of depletions three to five months later than the MODFLOW-UZF model for the first four years of simulation. This can be seen by comparison of the timing of the peaks in each curve. The difference is likely due to the MODFLOW-UZF model's consideration of more complex, three-dimensional flow patterns. In modeling three-dimensional flow through a heterogeneous system, depletions can begin impacting the stream network at multiple locations, including the tributaries, simultaneously. The Glover-Balmer solution predicts depletion only at the location specified by the idealized nearest distance to the river. In comparison to that for Field 1, the fallowing of Field 2 which is further from the river has a more significant impact on the timing of depletion predicted by the Glover-Balmer solution. This trend also is seen in examples that follow.

Figure 4.5A shows that the Glover-Balmer solution under-estimates stream depletion compared to the MODFLOW-UZF model for about the first three and a half years, whereupon it begins to over-estimate. The total stream depletion volumes show that the Glover-Balmer solution over-estimates the MODFLOW-UZF prediction of stream depletion by about 100,000 m^3, which is equivalent to a depth of about 0.4 m on the field. This is a much smaller depth than the 2 m over-estimation for Field 1, but still is considerable. The percentage of cumulative stream depletion shown in Figure 4.5B indicates that the Glover-Balmer solution under-predicts depletion for about the first six years, then it begins to over-predict while the MODFLOW-UZF model predicts depletion to cease. After simulation of about six years, the Glover-Balmer method begins over-estimating stream depletion increasingly with time in relation to MODFLOW-UZF model.

Similar to Figure 4.2C, Figure 4.5C shows that water table elevations vary most within grid cells furthest from the river (and closest to the fallowed field) and decreasingly vary as distance from the river is minimized. The change in water table elevation is shown for more grid cells for Field 2 than Field 1 because Field 2 is further from the river, meaning more grid cells lie in a straight-line path between the field and river. The maximum changes in water table elevation for cells near Field 2 are smaller than for grid cells near Field 1 because the irrigation volume is larger for Field 1. Thus, if a larger equivalent depth of water is removed from a field, one could expect a larger change in the water table elevation. Longer timespans are required for the change in water table elevation to reach zero for grid cells near Field 2 compared to those near Field 1. This could be due to generally less transmissive aquifer materials between Field 2 and the river. However, like Figure 4.2C, Figures 4.5C shows that the majority of changes in water table elevation cease between the third and fourth years of simulation. This again shows that water table elevations tend to recover within a few months of the last stress event.

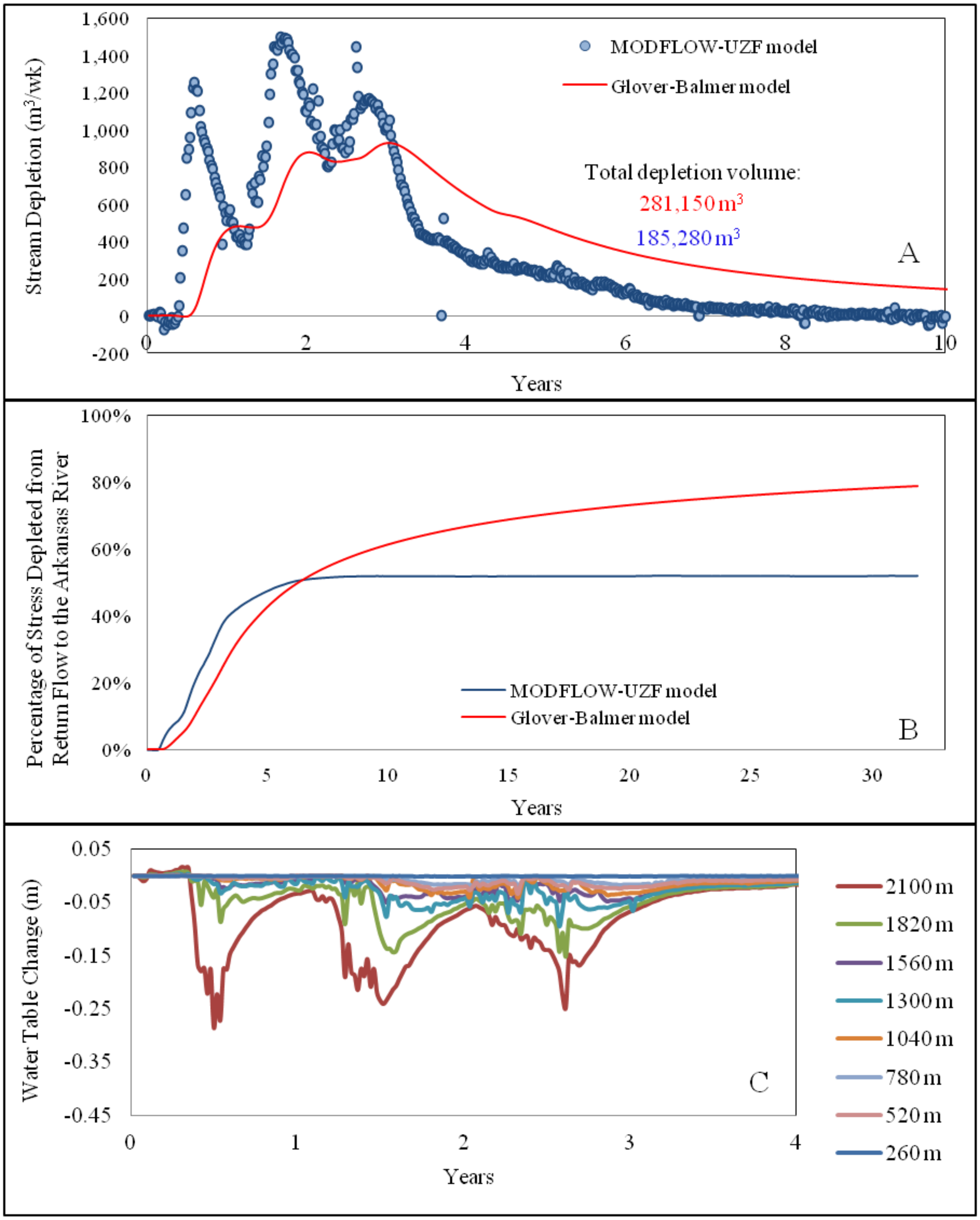


Figure 4.5. (A) The amount of stream depletion occurring at each timestep throughout the 32-year simulation period, as predicted by the Glover-Balmer solution and MODFLOW-UZF model, (B) the cumulative depletion expressed as a percentage of the total fallowed volume, and (C) the change in water table elevation for each cell in a straight-line path from the Arkansas River to the fallowed field.

The change in upflux rates to ET between the MODFLOW-UZF baseline and fallow simulations for Field 2 were not obtained, so a plot similar to Figure 4.3 is not available for Field 2. Although Figure 4.6 shows three isolated cases, one can imagine the complex, compounding changes in upflux to ET and total ET that can occur when altering irrigation water application to an array of fields in close proximity to one another simultaneously. The Glover-Balmer solution is not able to account for changes in hydrologic components besides stream depletion, and cannot estimate spatial impacts like those shown in Figure 4.6.

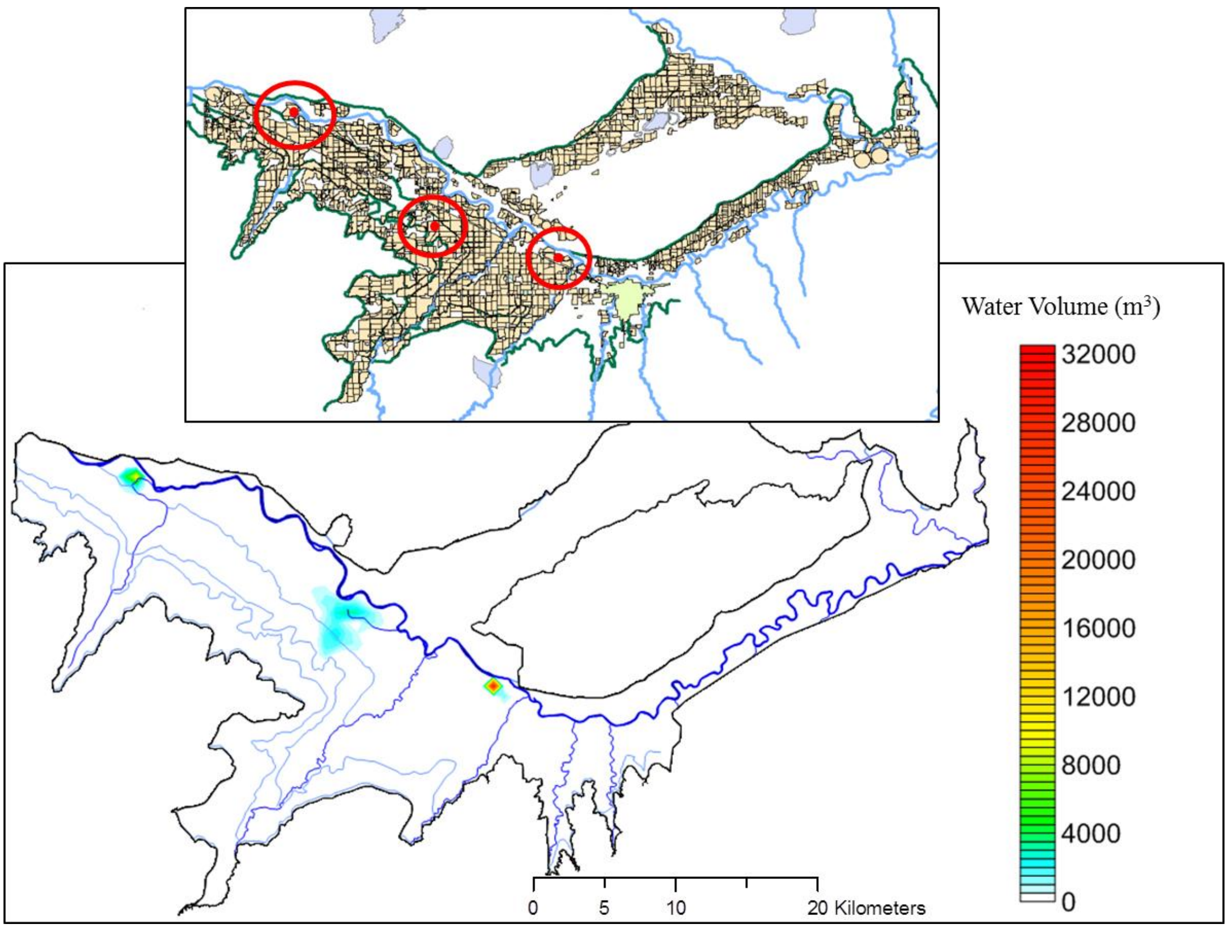


Figure 4.6. The difference in upflux to ET over the 32-year simulation period predicted by MODFLOW-UZF for baseline conditions and for a three year-long fallowing scenario.

Fields 1 and 2 are examples of the initial comparisons of the MODFLOW-UZF model to the Glover-Balmer solution. Results show that the Glover-Balmer solution tends to overestimate stream depletion in comparison to the MODFLOW-UZF model, which is consistent with the studies described in Chapter 2. Gates et al. (2012) showed that irrigation applications can vary significantly in the LARV, and results from Fields 1 and 2 show that the total volume of stream depletion overestimated by the Glover-Balmer solution in comparison to the MODFLOW-UZF prediction also can vary drastically. This has implications in real-world lease-fallowing cases where an overestimation on the order of 100,000 m^3 might have substantially more severe economic and environmental impacts than an overestimation on the order of 10,000 m^3.

4.1.2. One-year fallowing scenarios

Previously-discussed fallowing scenarios were applied within the first three years of the MODFLOW-UZF model simulation and Glover-Balmer solution. The first few years of the simulation period are relatively wet hydrologic years. However, the model also encompasses a drought period - with the driest years being 2002 and 2003. Additional scenarios were defined to explore the selection of relatively dry, wet, and average hydrologic conditions for fallowing the same field. The criteria used in selecting each year were the annual total precipitation amount and yearly canal flowrates. Each one-year fallowing scenario is simulated with the MODFLOW-UZF model and solved with the Glover-Balmer method to isolate the effects of fallowing for that single year. This means that three separate simulations were run for each considered. The dry, average, and wet years selected were 2003, 2008, and 1999, respectively.

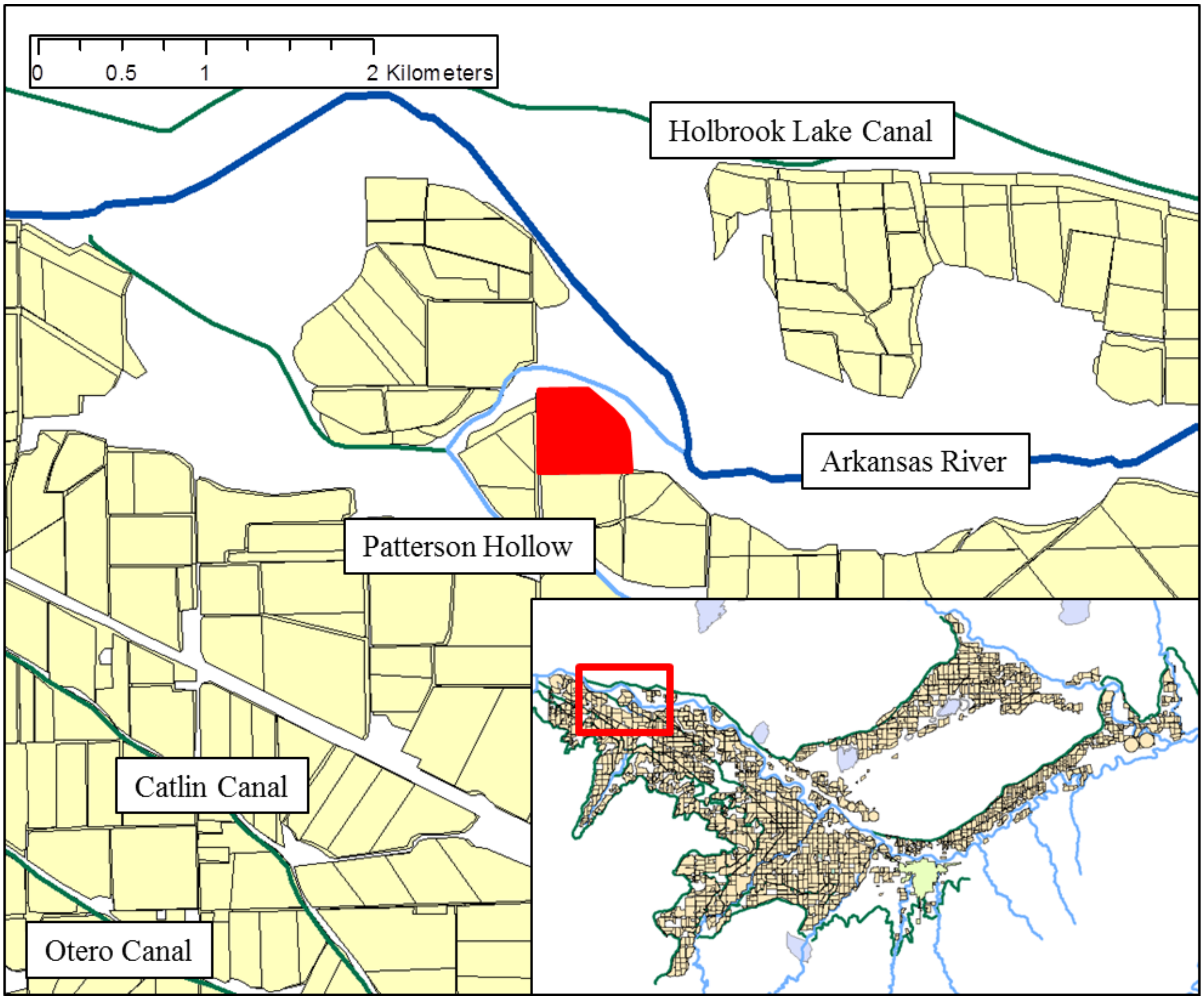


Figure 4.7. Location of Field 3 within the LARV.

Field 3 lies 300 m from the Arkansas River (relatively close), and has an area of 13.8 hectares (35 acres) as shown in Figure 4.7. Stream depletion estimates from the Glover-Balmer solution and simulation with the MODFLOW-UZF model are compared for the three separate-fallowing years. Weekly stream depletion values plotted for each year in Figure 4.8. Weekly depletion estimates and total depletion volumes from the Glover-Balmer solution and the MODFLOW-UZF model match relatively well for Field 3. Total depletion volumes depicted in Figure 4.8 show that that the volume applied to the field each year can vary significantly within the MODFLOW-UZF simulation. It also can be seen from Figure 4.8 that the difference between total depletion volumes estimated by the Glover-Balmer method and the MODFLOW-UZF model become larger as the total depletions become larger. This trend is also true of results for Fields 1, 2, and 4. This could be due to a magnification of errors in assumptions made by the Glover-Balmer solution as the value of Q increases. It suggests that additional caution should be incorporated when applying the Glover-Balmer method for removal of larger water volumes.

As seen in the changes of water table elevation for Fields 1 and 2, varying volumes of irrigation water removed by fallowing create varying effects on hydrologic components and stream depletion. Varying fallowing practices on a single field affect a variety of hydrologic components, each with a complex, non-linear response. For example, ET rates may not change drastically if the water table is lowered from 1 m below the ground surface to 1.5 m, but will probably change much more if it is lowered to 3 m. This depth is greater than the rooting depth of most plants, and additionally, larger changes to the water table due to altered water management on one field can have a significant impact on the ET of surrounding fields (as shown in Figure 4.6). The complexity increases as fallowing regimes are applied to a variety of fields over a regional scale. The MODFLOW-UZF model can approximately account for such hydrologic complexities, but the analytical Glover-Balmer solution does not. For Field 3, the Glover-Balmer solution underestimates stream depletion for all three fallowing years. Though somewhat uncommon, this outcome also is seen in other scenarios. It is hypothesized that the MODFLOW-UZF model predicts greater stream depletion than the Glover-Balmer solution due to a reduced simulated gradient towards the river is compared to the baseline. If the gradient is reduced in comparison to the baseline scenario, less stream accretion will occur.

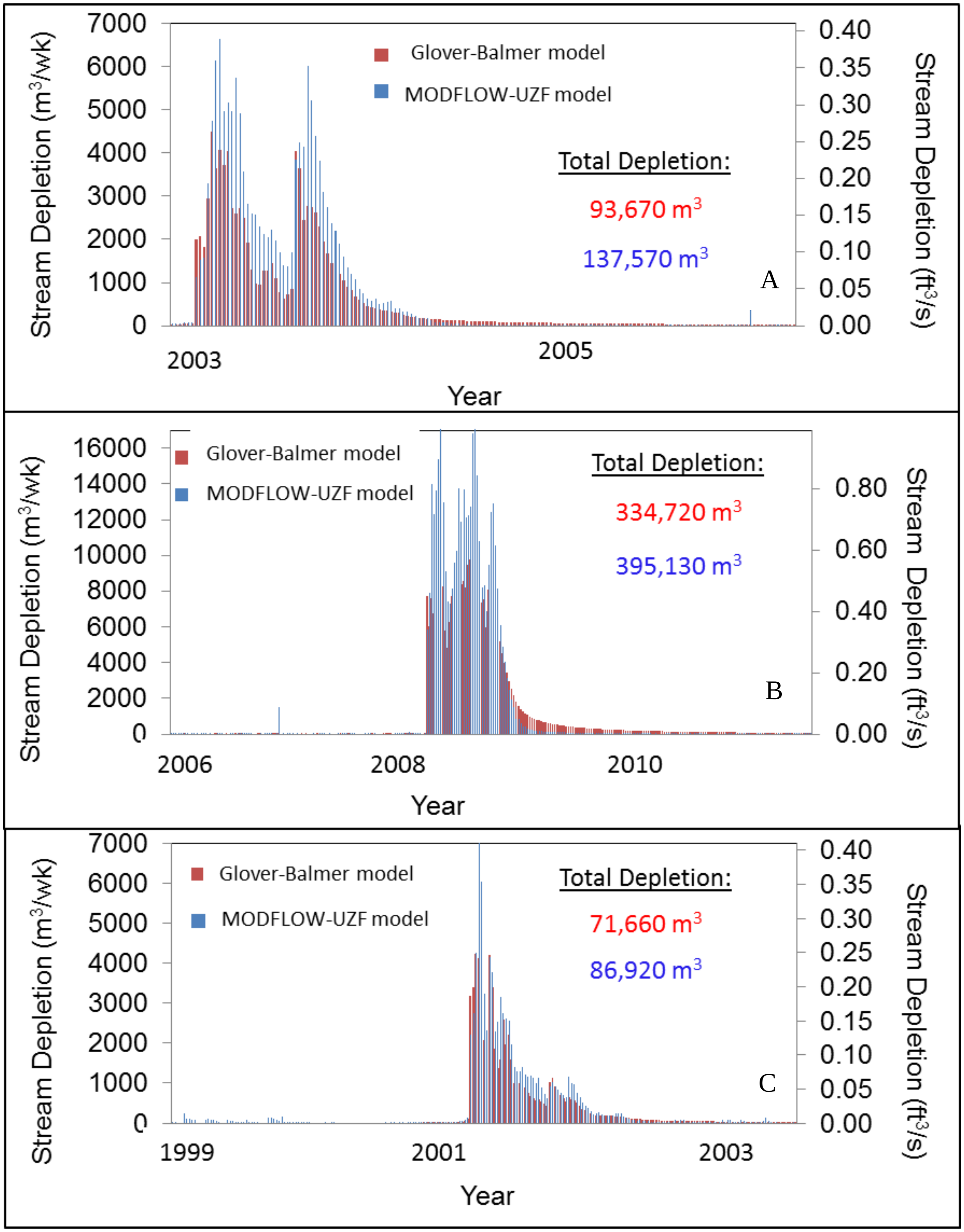


Figure 4.8. Weekly stream depletion estimates from the MODFLOW-UZF model and the Glover-Balmer solution for the case of fallowing Field 3 within (A) a relatively dry hydrologic year (2003), (B) an average year (2008), and (C) a relatively wet year (1999).

Field 4, located adjacent to Field 3, is about the same distance from the Arkansas River, but is much smaller; at about 3.2 hectares (8 acres). The location is shown in Figure 4.9. Stream depletion results for Field 4 are shown in Figure 4.10.

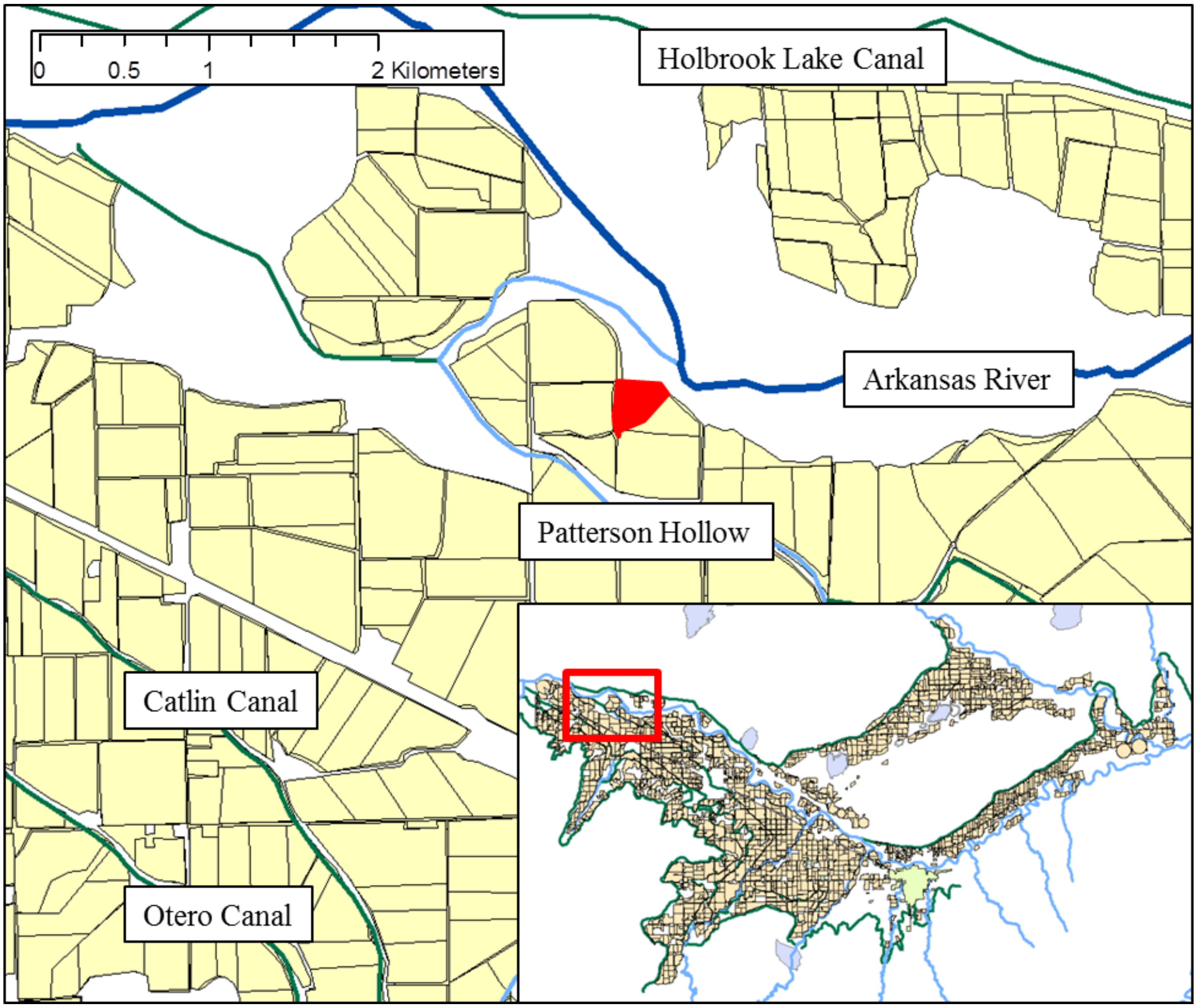


Figure 4.9. The location of Field 4 within the LARV.

Though total stream depletion estimates by the MODFLOW-UZF model the Glover-Balmer solution are the same during fallowing in the dry year (Fig. 4.10A), the Glover-Balmer solution predicts greater total stream depletion than the MODFLOW-UZF model for the average and wet years. This may be caused by the non-linear responses of the hydrologic system in response to the removal of different irrigation volumes during fallowing. However, the estimates of total stream depletion by the two methods are relatively close in each of the three comparisons, and week-by-week estimates from both models match fairly closely. Unlike Field 3, the Glover-Balmer solution slightly overestimates stream depletion compared to the MODFLOW-UZF model during the average and wet year fallowing in Field 4.

As removed irrigation volumes increase during the average and wet hydrologic years, residual stream depletion predicted by the Glover-Balmer solution extends for about 1 year longer than that of the MODFLOW-UZF model. This trend appears to be consistent with results from the three-year fallowing scenarios. It appears that as the volume of irrigation water removed increases, the superposition application predicts longer, more substantial depletion than is predicted by the MODFLOW-UZF model. This suggests that the use of superposition with the Glover-Balmer solution may lead to greater overestimation of stream depletion as the fallowing volume and timespan are increased beyond about 1 year. This most likely is due to the simplifying assumptions made in the Glover-Balmer solution, such as a homogeneous aquifer and perfect stream-aquifer connection.

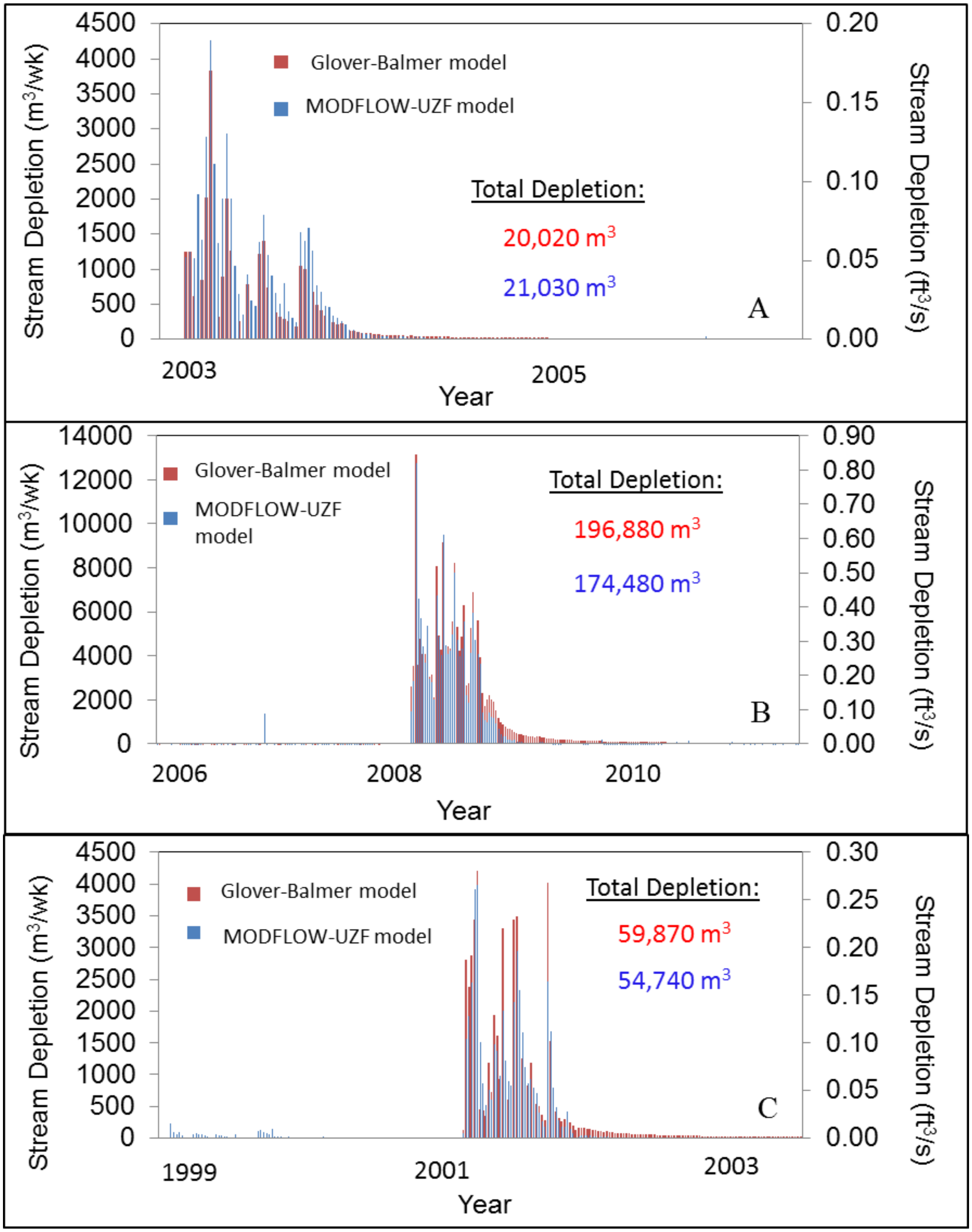


Figure 4.10. Weekly stream depletion estimates from the MODFLOW-UZF model and the Glover-Balmer solution for the case of fallowing Field 4 within (A) a relatively dry hydrologic year (2003), (B) an average year (2008), and (C) a relatively wet year (1999).

The one-year fallowing scenarios show that the Glover-Balmer solution can reasonably estimate stream depletions in relatively close proximity to the Arkansas River (less than about 500 m). However, some discrepancies between the Glover-Balmer solution and MODFLOW-UZF model predictions arise, including a case where the Glover-Balmer solution underestimates stream depletion (Field 3) in comparison to the MODFLOW-UZF model and one in which it overestimates (Field 4). The case of overestimation is consistent with the three-year fallowing scenarios and the findings of previous studies presented in Chapter 2.

4.2. Results for water addition scenarios

4.2.1. Scenarios with water addition to the saturated zone

4.2.1.1. Individual scenarios with water addition to the saturated zone

Field 5 represents a water addition scenario relatively close to the Arkansas River. The stressed cell within the field resides about 250 m from the Arkansas River, and the field associated with the stressed cell is shown in Figure 4.11. Predictions of stream accretion for this scenario are shown in Figure 4.12.

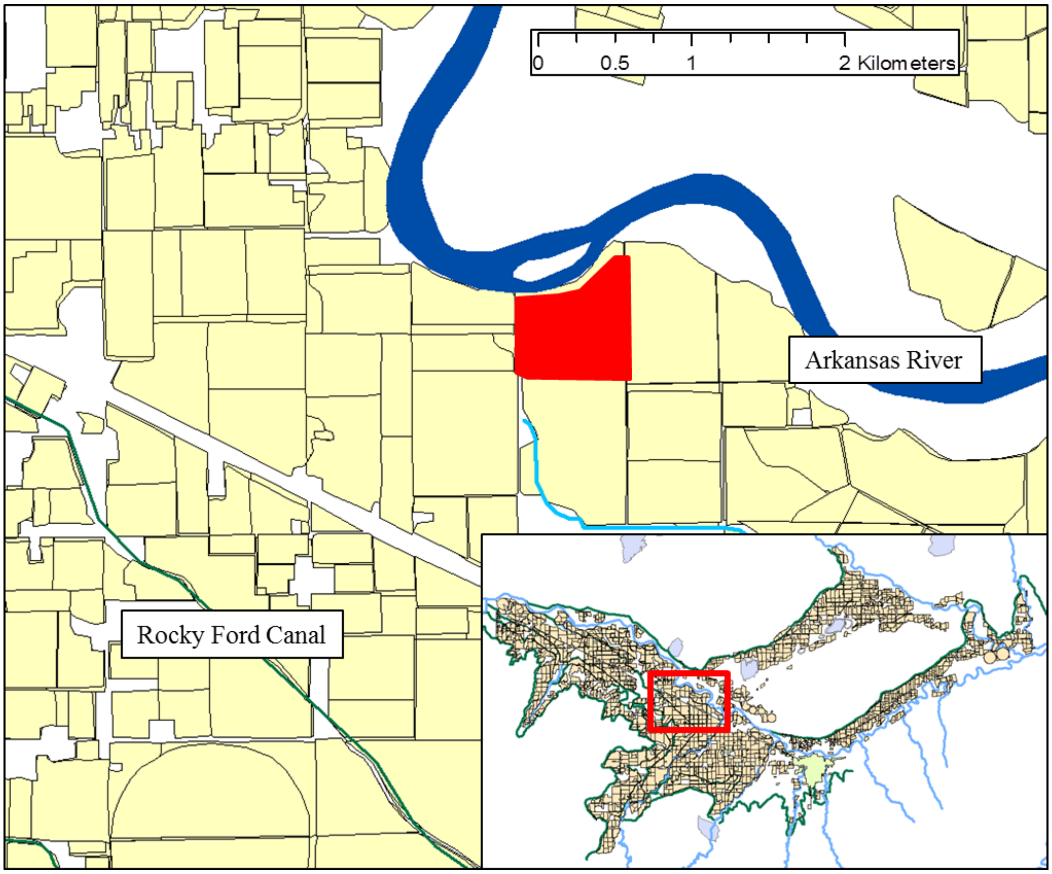


Figure 4.11. The location of Field 5 within the LARV.

As a water addition scenario, stream accretion (negative depletion) is expected. Figure 4.12A is a bar plot of the location and magnitude of accretion to the stream network, as predicted by the MODFLOW-UZF model. Since the stressed cell is relatively close to the Arkansas River and the water table tends to slope towards the river, water accretes only to the river; yet the pattern is spread out along the main stem of the river. Figure 4.12B shows total stream accretion with respect to time, and Figure 4.12C shows the percentage of the total stress volume predicted to accrete to the Arkansas River and tributaries with respect to time. It is seen from Figure 4.12B that the Glover-Balmer solution prediction of total accretion closely resembles that of the MODFLOW-UZF model. Figure 4.12C highlights the similarities in timing and volume of accretion between the two models, although the MODFLOW-UZF model predicts accretion more quickly for about 8 months. As postulated in the discussion of the one-year lease-fallowing scenarios, accretion may occur more quickly in the MODFLOW-UZF model because of its ability to estimate transient, three-dimensional flow. The Glover-Balmer solution considers flow through a homogenous system at a single specified distance.

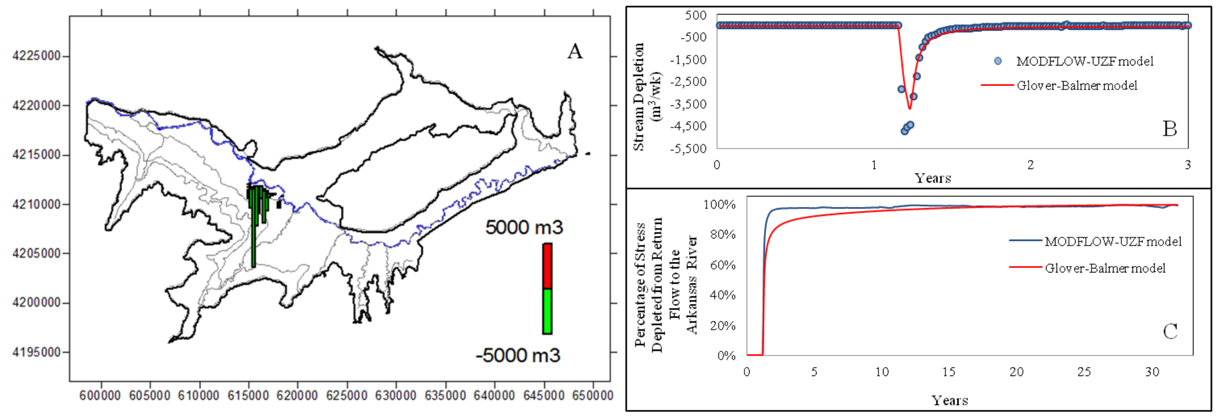


Figure 4.12. (A) Bar plot of stream accretion (negative depletion) as predicted by the MODFLOW-UZF model for Field 5, (B) the time period in which stream accretion occurs within the 32-year simulation period, as predicted by the Glover-Balmer solution and MODFLOW-UZF model, and (C) the cumulative accretion expressed as a percentage of the total stress volume.

Figure 4.13A shows the water table elevation change for the grid cells between the stressed cell and the Arkansas River. The positive change in water table elevation indicates an increase in water table elevation compared to the baseline. An increase is expected for water addition scenarios. Water table elevation change is relatively small in comparison to grid cells further from the river, but is consistent with changes in other grid cells at about the same distance from the Arkansas River. The total change in upflux to ET for each MODFLOW-UZF model grid cell is shown in Figure 4.13B. Similar to the water table elevation change, positive values indicate an increase compared to the baseline. An increase in upflux to ET is possible as the water table rises and plants are predicted to obtain more water from the saturated zone.

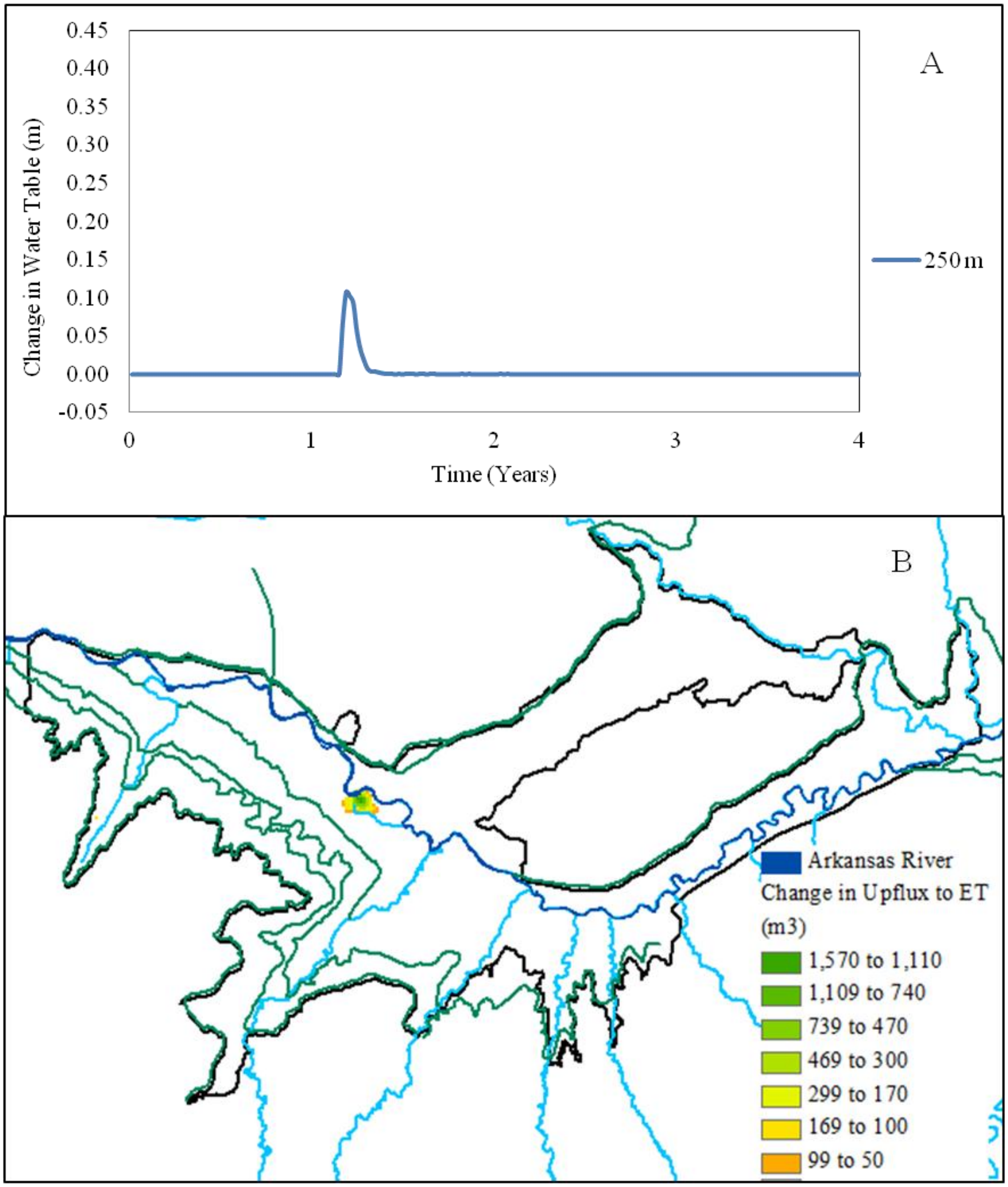


Figure 4.13. (A) The water table elevation change for grid cells in a straight-line path between the stressed cell and Arkansas River, and (B) the total change in upflux to ET for each grid cell for the 32-year simulation period.

Field 6 is relatively far from the Arkansas River, with a straight-line distance of about 2600 m. The location within the LARV is shown in Figure 4.14.

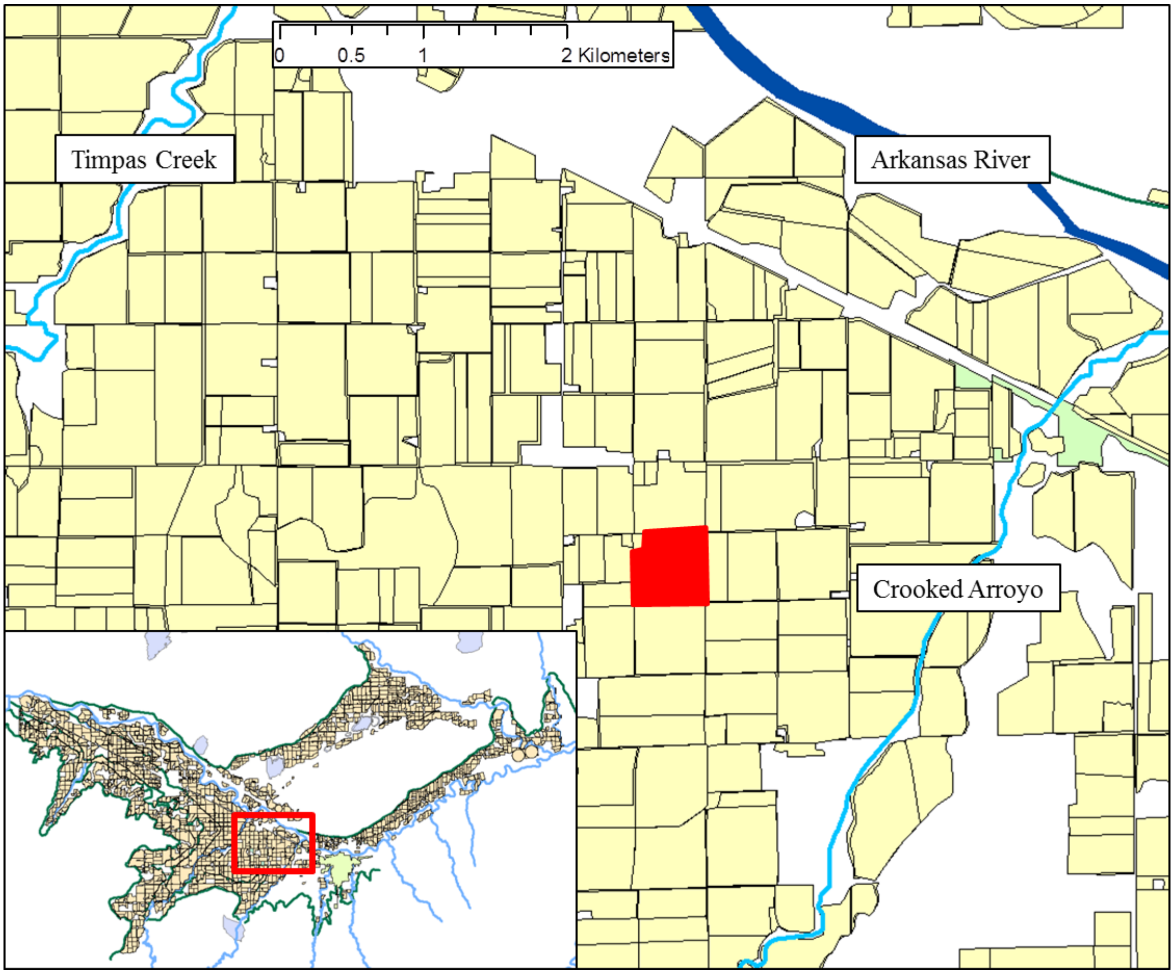


Figure 4.14. The location of Field 6 within the LARV.

Representing another water addition scenario, Figure 4.15A shows that accretion occurs to Timpas Creek, Crooked Arroyo, and the Arkansas River, spread out over several kilometers. In comparison to similar plots for different examples, the scales must be taken into consideration as they have been adjusted to see sufficient details in each plot. It can be seen in Figure 4.15B that the timing of cumulative accretion occurs similarly in both models until about the fifth year of simulation. Estimates of total accretion diverge as the MODFLOW-UZF model predictions of increased net ET, canal interception and groundwater storage cause accretion estimates to diminish. Accretions take longer to reach the stream network in comparison to predictions for

Field 5. Additionally, accretions are more spread out and do not reach the river as directly as they are predicted to at close distances. The Glover-Balmer model predicts a significantly longer accretion period, which is due to the relatively large straight-line distance from the Arkansas River. Since distance is the only squared value in the Glover-Balmer solution, the solution's predictions are most sensitive to changes in *x*. Figure 4.15C shows that the Glover-Balmer solution overestimates stream accretion significantly in comparison to the MODFLOW-UZF model.

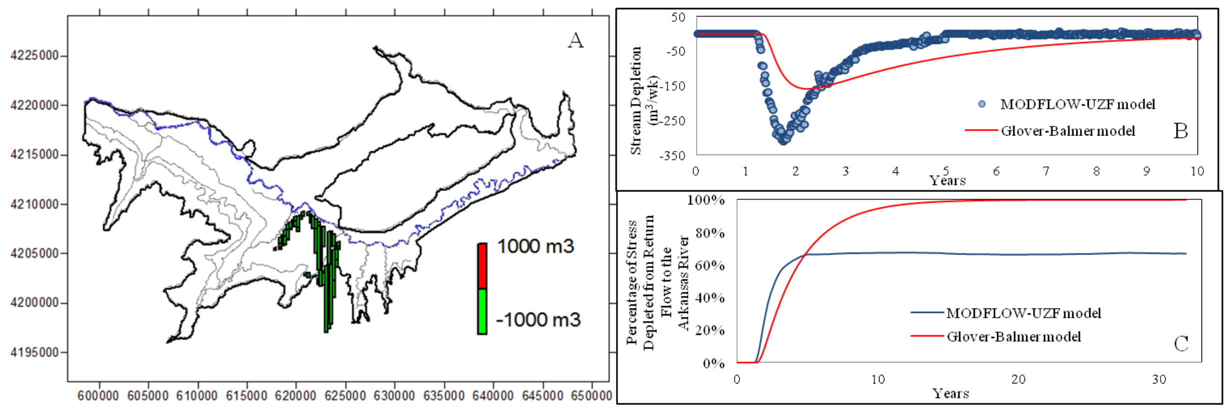


Figure 4.15. (A) Bar plot of stream accretion (negative depletion) as predicted by the MODFLOW-UZF model for Field 6, (B) the time period in which stream accretion occurs within the 32-year simulation period, as predicted by the Glover-Balmer solution and MODFLOW-UZF model, and (C) the cumulative stream accretion expressed as a percentage of the total stress volume.

Water table elevation change, shown in Figure 4.16A, indicate an increase in water table elevations between the first and second year of simulation when the stress is applied. Similar to plots for Fields 1 and 2, Figure 4.16A shows that grid cells furthest from the Arkansas River (and closest to the stressed grid cell) experience the largest water table elevation change. Grid cells experiencing the largest water table elevation change are predicted to require the most time to return to baseline levels, and water table elevations are predicted to recover almost completely within about six months. The total change in upflux to ET for each grid cell is shown in Figure

4.16B where it can be seen that changes in upflux to ET occur over a much wider area than was seen in results for Field 5. However, the magnitudes of changes in upflux to ET surrounding Field 6 are lower than those seen around Field 5. This is most likely due to the larger distance and groundwater travel time to the stream network allowing changes in upflux to ET to affect a larger area. Changes in upflux to ET occur in fields adjacent to the stressed grid cell, and show the regional effects that can occur while altering water management on a field. In comparison to regional-scale hydrologic processes, the volume expressed in Fig. 4.16B are quite small due to the relatively small stress event. However, the outcome is still important to consider.

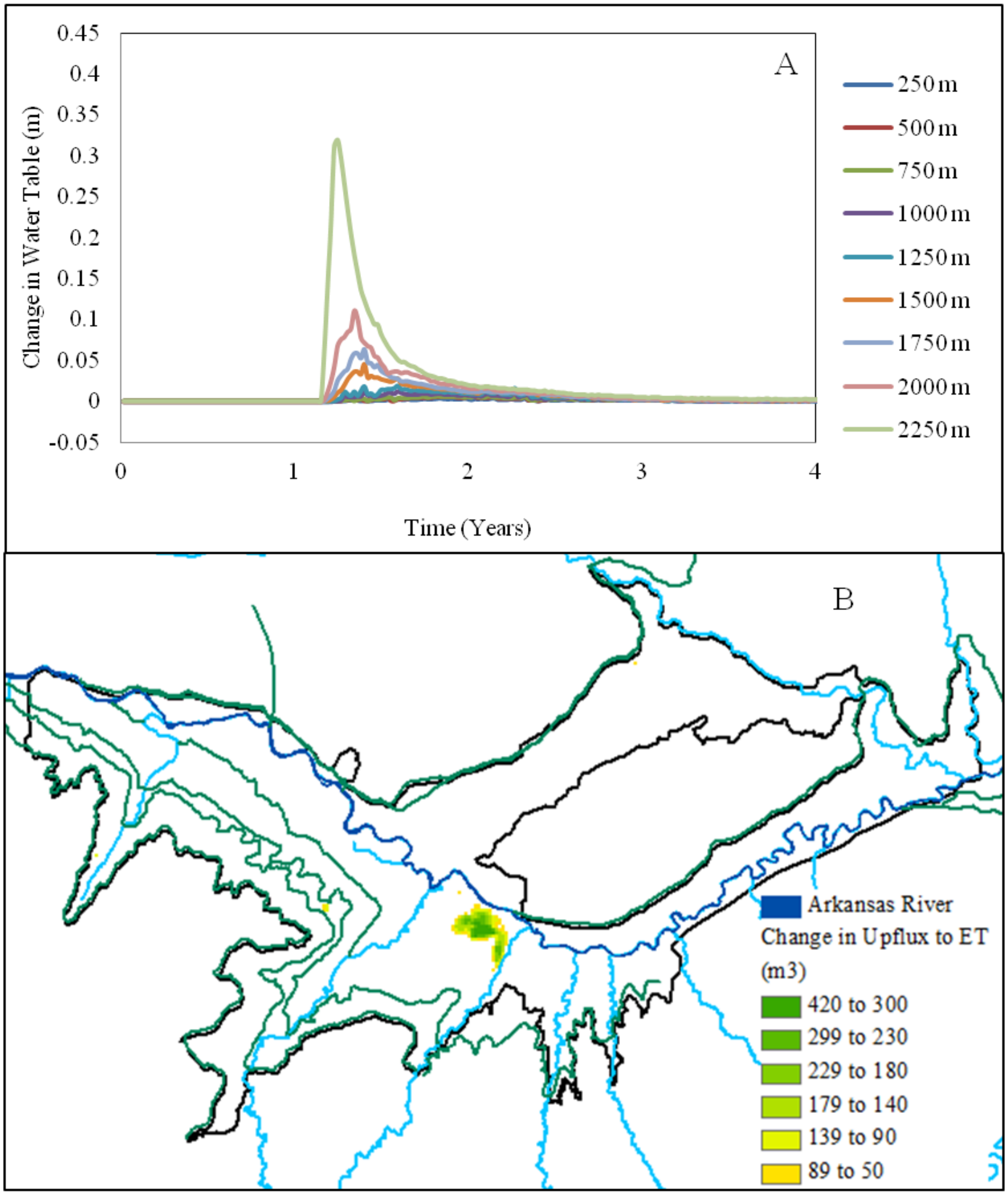


Figure 4.16. (A) The water table elevation change for grid cells in a straight-line path between the stressed cell and Arkansas River, and (B) the total change in upflux to ET for each grid cell in the 32-year simulation period.

4.2.1.2. Summary of scenarios with water addition to the saturated zone

As water is added to a given model cell, the water table is predicted to rise and become mounded in and around the stressed cell. Figure 4.17 shows the change in net ET (unsaturated zone ET plus upflux to ET) as compared to the baseline MODFLOW-UZF scenario for all scenarios of water addition to the saturated zone and each point represents one scenario. The change in net ET is expressed as a percentage of the total stress volume (25 acre-feet) to show the portion of stress predicted to be consumed as ET. Figure 4.17 and similar subsequent plots for other hydrologic features show the portion of the stress volume attributed to a given hydrologic component in the MODFLOW-UZF simulation. For most addition scenarios the net ET values tend to increase compared to the baseline MODFLOW-UZF model simulation. Positive values indicate an increase in total net ET compared to the baseline. Generally, about 0 – 20% of the stress volume is consumed as net ET. If about 20% of the stress volume is attributed to ET, this can lead to notable differences in stream depletion estimates between the Glover-Balmer solution and MODFLOW-UZF model. Negative values indicate a decrease in net ET compared to the baseline case and are somewhat exceptional. Most of the negative values are within about 10%, which may be within the range of uncertainty in values. Negative values indicate the reduction in ET from the unsaturated zone is predicted to be larger than the increase in ET from the saturated zone.

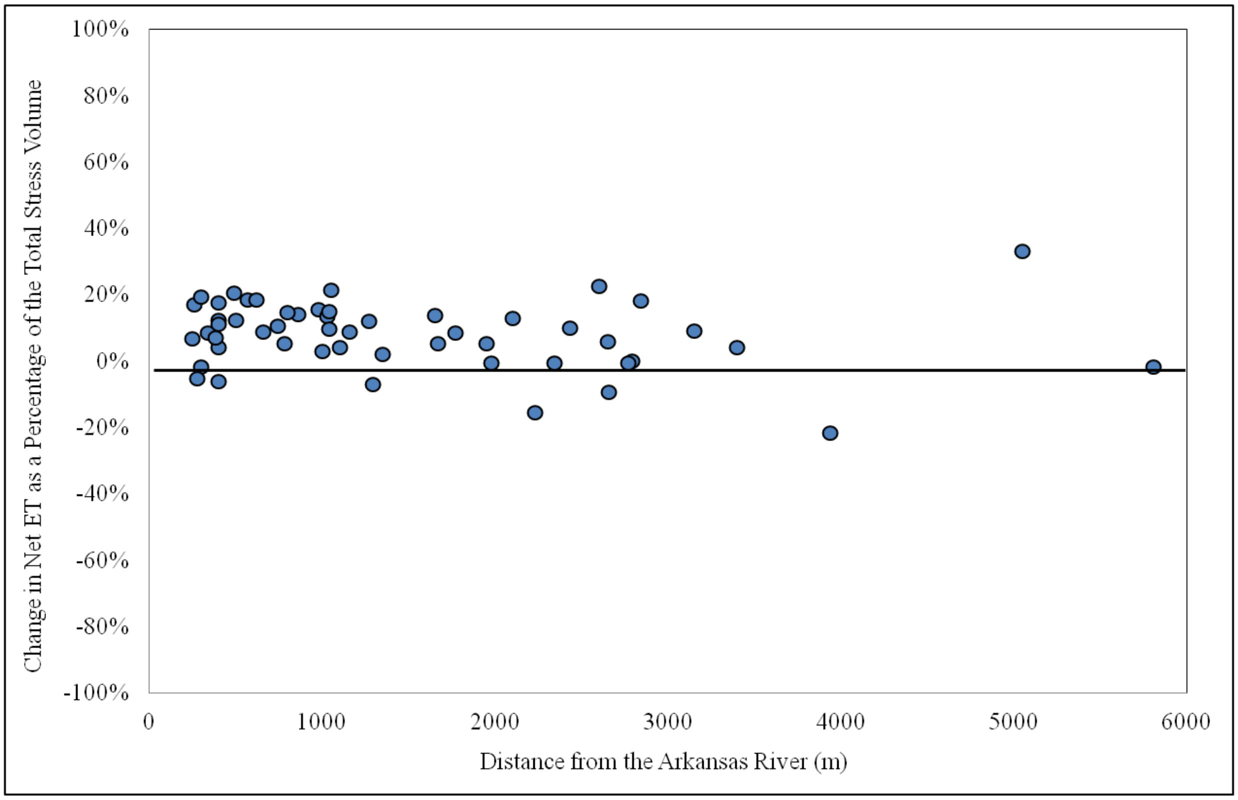


Figure 4.17. The change in net ET predicted by the MODFLOW-UZF mode as a percentage of stress volume by water addition versus distance to the Arkansas River.

Fields adjacent to irrigation canals receiving water addition stress can accrete significant amounts of the stress volume to the canals themselves. Stress volume accreted to a canal does not become accretion to the stream network in the MODFLOW-UZF model. Thus, in scenarios where significant accretion occurs to a canal, comparisons of accretion estimates between the MODFLOW-UZF model and the Glover-Balmer solution will not match well because the Glover-Balmer solution does not consider flow to canals. Figure 4.18 shows the stress volume as accretion to canals for each scenario of water addition to the saturated zone. For most scenarios, canal accretion is estimated to be less than 20% of the stress volume. However, in certain cases where stressed cells are relatively close to canals accretion prediction in the MODFLOW-UZF model can range from 40 – 90% of the stress volume. In these cases, significant differences in stream depletion estimates arise between the Glover-Balmer solution and the MODFLOW-UZF model. Positive values shown in Figure 4.18 indicate a decrease in canal seepage compared to the baseline. This occurs when the water table initially is lower than the canal and remains lower after the stress event. The influence of irrigation canals on estimates of stream depletion/accretion in comparison to the Glover-Balmer solution have not been considered in previous studies, but are shown to be potentially significant.

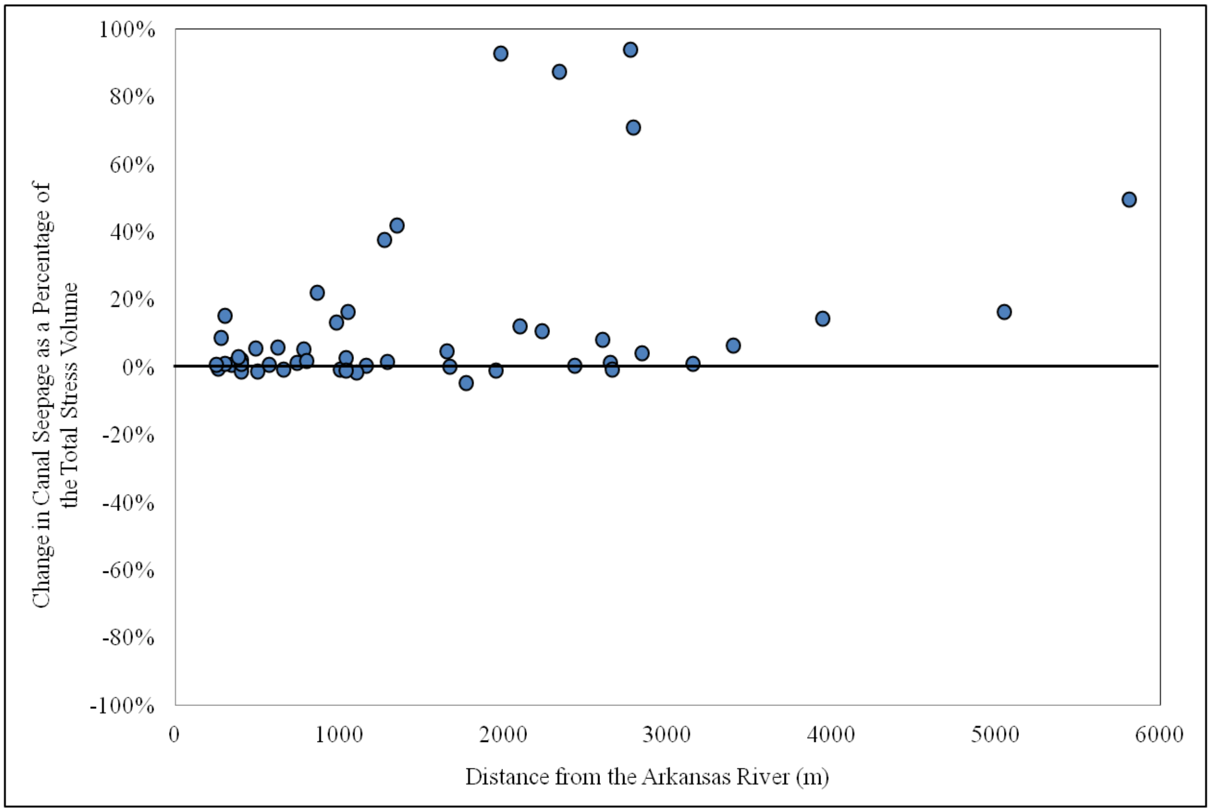


Figure 4.18. Change in canal interception predicted by the MODFLOW-UZF model as a percentage of the stress volume by water addition versus distance to the Arkansas River.

It is also possible for a portion of the stress volume to be stored within the subsurface where it would be neither intercepted by a canal or the stream network, nor used as ET. This volume of water, called groundwater storage, is accounted for by the MODFLOW-UZF model in its calculations of groundwater fluxes through grid cells. Groundwater storage change can be calculated indirectly by applying a water balance that includes stream accretion, net ET, and canal interception. Figure 4.19 displays the percentage of the stress volume predicted to groundwater storage for each scenario of water addition to the saturated zone. Positive values indicate an increase compared to the baseline scenario, meaning some of the water added as a stress remains in the subsurface as storage. In several scenarios the change in groundwater storage amount to more than 40 – 80% of the stress volume. These storage changes can lead to large differences in predictions by the Glover-Balmer solution and the MODFLOW-UZF model since the Glover-Balmer solution does not account for changes in groundwater storage. A relatively large amount of variability is present in Figure 4.19 due to the variable conditions in the LARV. Highly variable and transient water table elevations predicted by the model create variable and transient saturated and unsaturated zones, resulting in groundwater storage changes due to water addition stresses that also are highly variable. Negative values indicate a decrease in groundwater storage compared to the baseline case, and could be due to changes in the hydraulic gradient to create a condition that allows additional accretion to the stream network, canals, or consumption as ET.

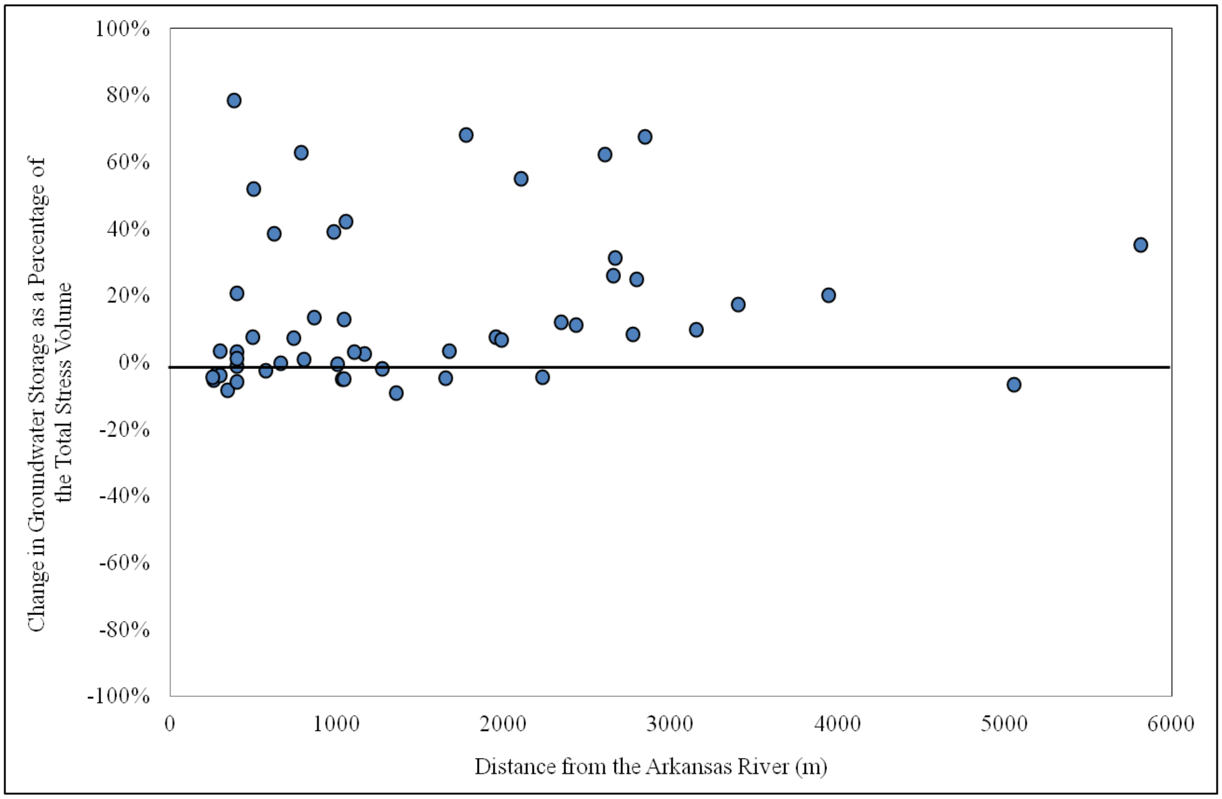


Figure 4.19. Change in groundwater storage predicted by the MODFLOW-UZF model as a percentage of stress volume by water addition versus distance to the Arkansas River.

To compare stream accretion estimates at the end of the 32-year simulation period, the ratio of the MODFLOW-UZF and Glover-Balmer percentages of total stress volume accreted to the stream network is plotted for each scenario in Figure 4.20. In the majority of cases, the Glover-Balmer solution predicts substantially greater stream accretion than does the MODFLOW-UZF model.

There are instances, however, in which stream accretion estimates by the Glover-Balmer solution match those by the MODFLOW-UZF model fairly well. It is especially possible for a relatively close match ($0.8 \leq$ MODFLOW% / Glover-Balmer% ≤ 1.2) to occur at locations relatively close to the Arkansas River (less than 0.5 to 1 km). Under such circumstances, the added water is relatively unaffected by ET, canal interaction, and groundwater storage change.

Close to the river such hydrologic processes do not greatly impede accretion to the river. At increasing distances from the river, it becomes more difficult to anticipate when the the Glover-Balmer accretion predictions will be close to those of the MODFLOW-UZF model due to increasing amounts of complexity in the physical system. Therefore, the ability of the Glover-Balmer solution to mimic more realistic conditions is highly variable. In some instances, its predictions deviate greatly from those of the more complex calibrated MODFLOW-UZF model. In a few cases, the Glover-Balmer solution under-predicts stream accretion in relation to the MODFLOW-UZF model. In such cases the MODFLOW-UZF model predicts increased accretion volumes (compared to the baseline case) greater than the stress volume. It is hypothesized that this is due to an increase of the water table gradient towards the river areas with large enough hydraulic conductivity to cause an increase in groundwater discharge toward the river over the simulation period that is larger than the stress volume.

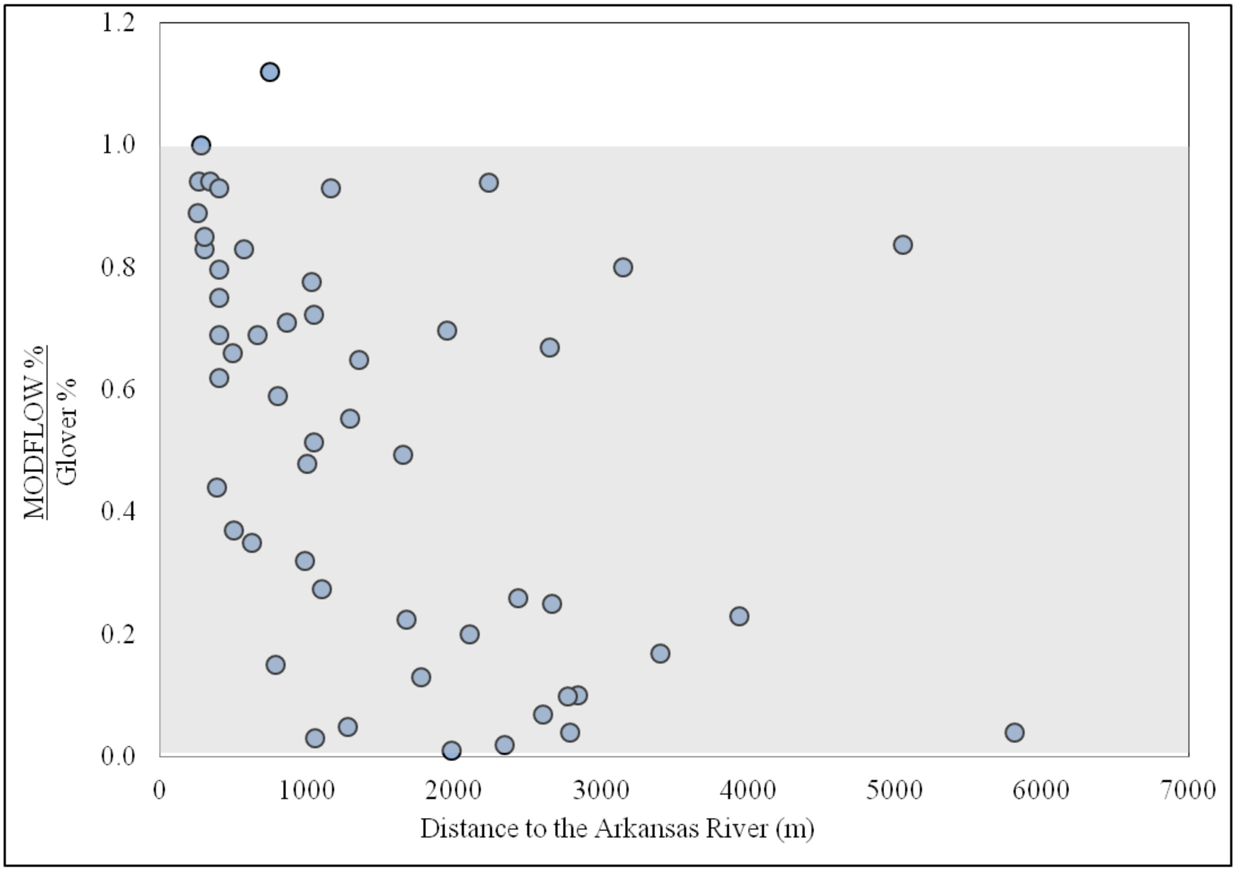


Figure 4.20. The ratio of the cumulative volume of stream accretion as a percentage of the stress volume predicted by the MODFLOW-UZF model divided by the cumulative volume of accretion as a percentage of the stress volume predicted by the Glover-Balmer method at the end of the 32-year simulation for 52 scenarios of water addition to the saturated zone versus distance from the Arkansas River.

Table 4.1 shows the percentage of scenarios in which the MODFLOW% / Glover-Balmer% ratio is between 0.8 and 1.2. Good comparisons between the two methods are less and less prevalent as the shortest straight-line distance from the Arkansas River increases. Predictions by the two methods are within 20% of each other in over half of the scenarios located within 0.5 km, and in about one quarter of those within 4 km. This implies that as distance from the river increases, the likelihood of the Glover-Balmer solution providing accretion estimates similar to those of the calibrated MODFLOW-UZF model decreases.

Table 4.1. The percentage of scenarios in which estimates of stream accretion estimates by the Glover-Balmer solution are within 20% of those of the calibrated MODFLOW-UZF model in relation to shortest straight-line distance from the Arkansas River.

Straight-line distance to the Arkansas River (km)	Percentage of scenarios in which $0.8 \leq$ MODFLOW% / Glover-Balmer% ≤ 1.2
≤ 0.5	57
≤ 1.0	43
≤ 2.0	30
≤ 4.0	26

In regards to overestimation of stream accretion by the Glover-Balmer solution, the timing at which overestimation begins is also of interest. Figure 4.21 shows the time after the water addition stress event at which the Glover-Balmer solution begins to overestimate stream accretion in relation to the MODFLOW-UZF model by at least 10%. A similar curve is supplied for overestimation by 20%. By about the 10th year of simulation, the Glover-Balmer solution overestimates stream accretion by at least 10% in about half of the scenarios. At the end of the 32-year simulation period, the Glover-Balmer method overestimates stream accretion by at least 10% in about 70% of the scenarios. Overestimation by at least 20% occurs in slightly over half of the scenarios by about the 22nd year of simulation, and increases only slightly until the end of the 32-year simulation period.

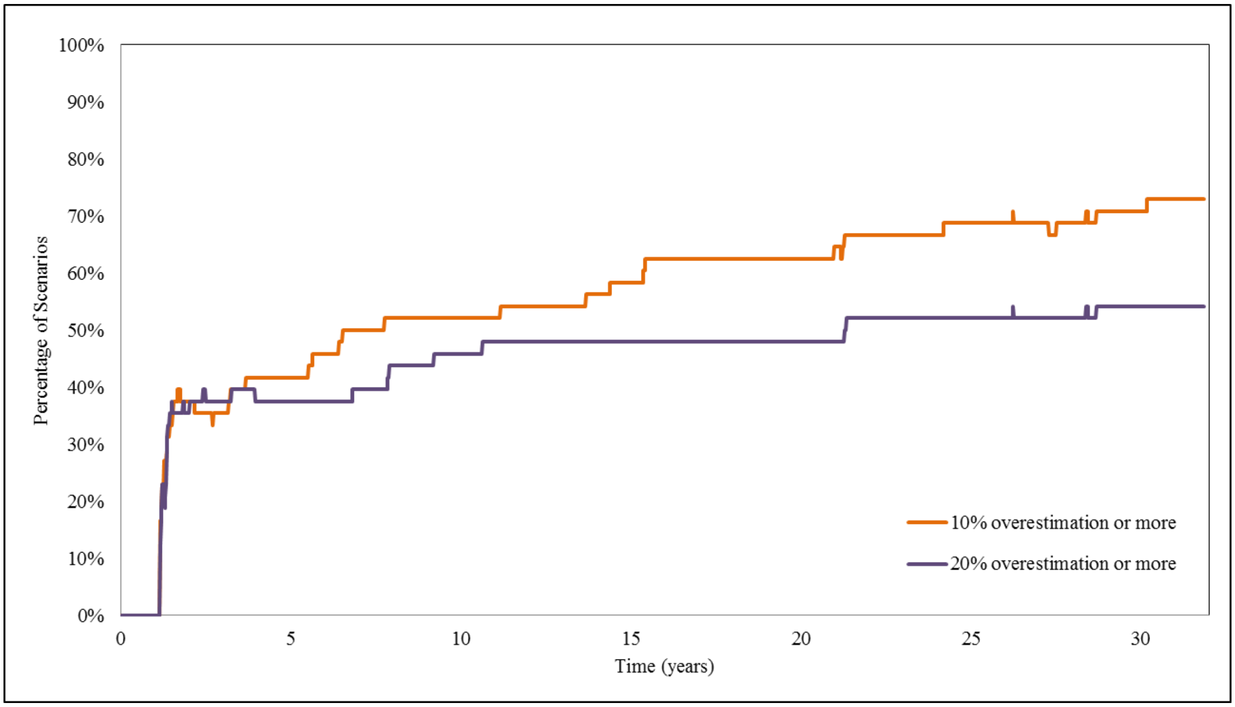


Figure 4.21. Percentage of scenarios in which the Glover-Balmer solution overestimates stream accretion in comparison to predictions by the calibrated MODFLOW-UZF model by at least 10% or 20% for water addition scenarios.

4.2.2. Scenarios with water addition to the ground surface

A summary of scenarios where water is added to fields at the ground surface is presented in Figure 4.22, which shows the ratio of stream accretion predicted by the MODFLOW-UZF model to that of the Glover-Balmer solution for 49 scenarios. The Glover-Balmer solution overestimates stream accretion in comparison to the MODFLOW-UZF model in all but one case. Figure 4.22 shows a trend of increasing overestimation by the Glover-Balmer solution as the shortest straight-line distance from the Arkansas River is increased. This relationship is more prevalent than in scenarios with water addition to the saturated zone. This implies the possibility that the unsaturated zone plays a role in controlling return flows farther from the river. This could be true if additional water is used by vegetation as it travels through the saturated zone (as compared to scenarios of water addition to the saturated zone), or that additional water is attributed to groundwater storage change. However, a definitive conclusion is difficult to discern since several scenarios involved a decreased stress volume to ensure adequate infiltration. The methodology employed in applying water stress to the ground surface is similar to that of a recharge pond, which sometimes are used as a means of augmenting aquifer depletion caused by groundwater pumping in the LARV. As mentioned previously, scenarios of water addition to the ground surface were not explored in the same detail as scenarios of water addition to the saturated zone, so results are limited to those shown in Figure 4.22.

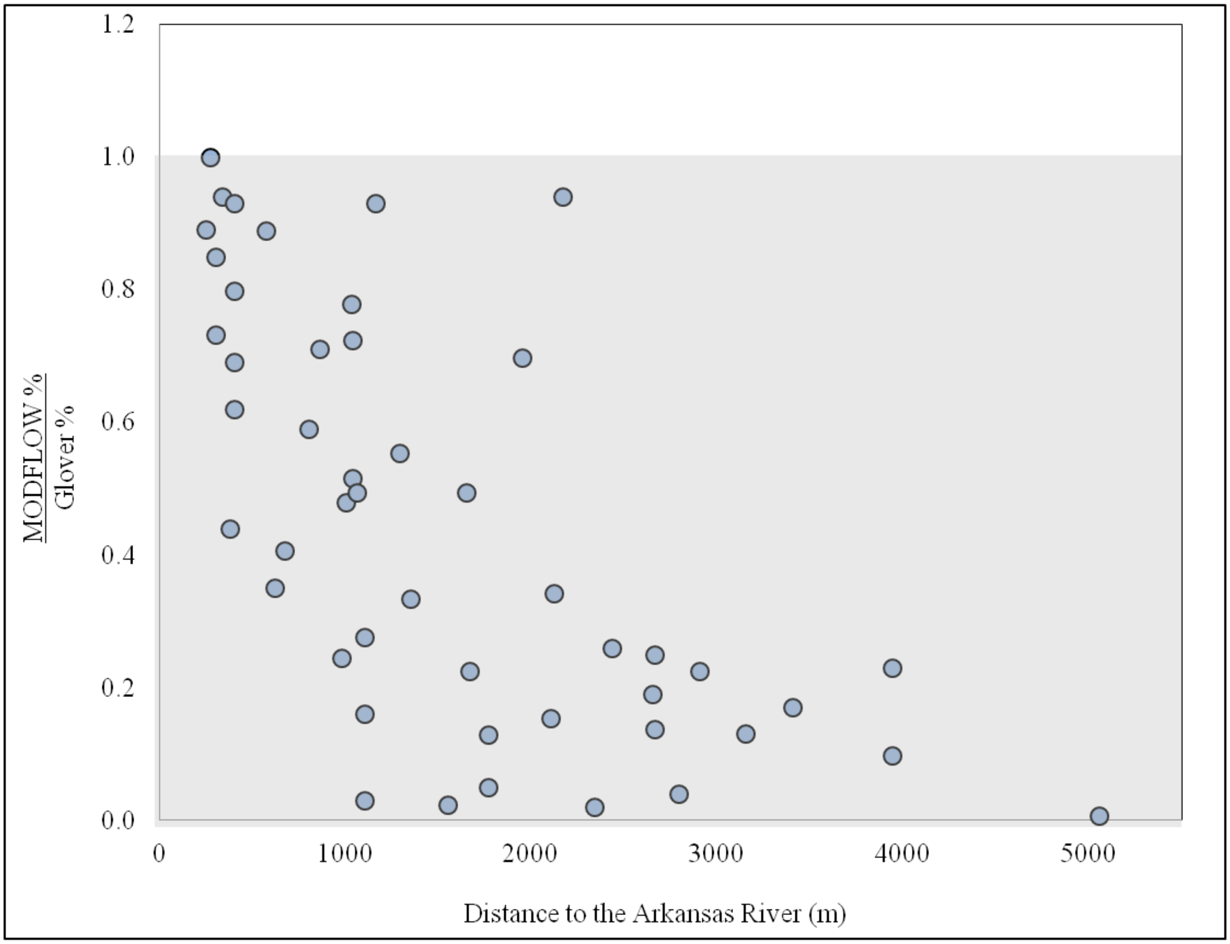


Figure 4.22. The ratio of the cumulative volume of stream accretion as a percentage of the stress volume predicted by the MODFLOW-UZF model divided by the cumulative volume of accretion as a percentage of the stress volume predicted by the Glover-Balmer method at the end of the 32-year simulation for 49 scenarios of water addition to the ground surface versus distance from the Arkansas River.

4.3. Scenarios of water extraction from the saturated zone

4.3.1. Individual Scenarios of water extraction from the saturated zone

Field 7 is an an extraction scenario relatively close to the main stem of the Arkansas River, about 500 m away. The location of Field 7 within the LARV is shown in Figure 4.23.

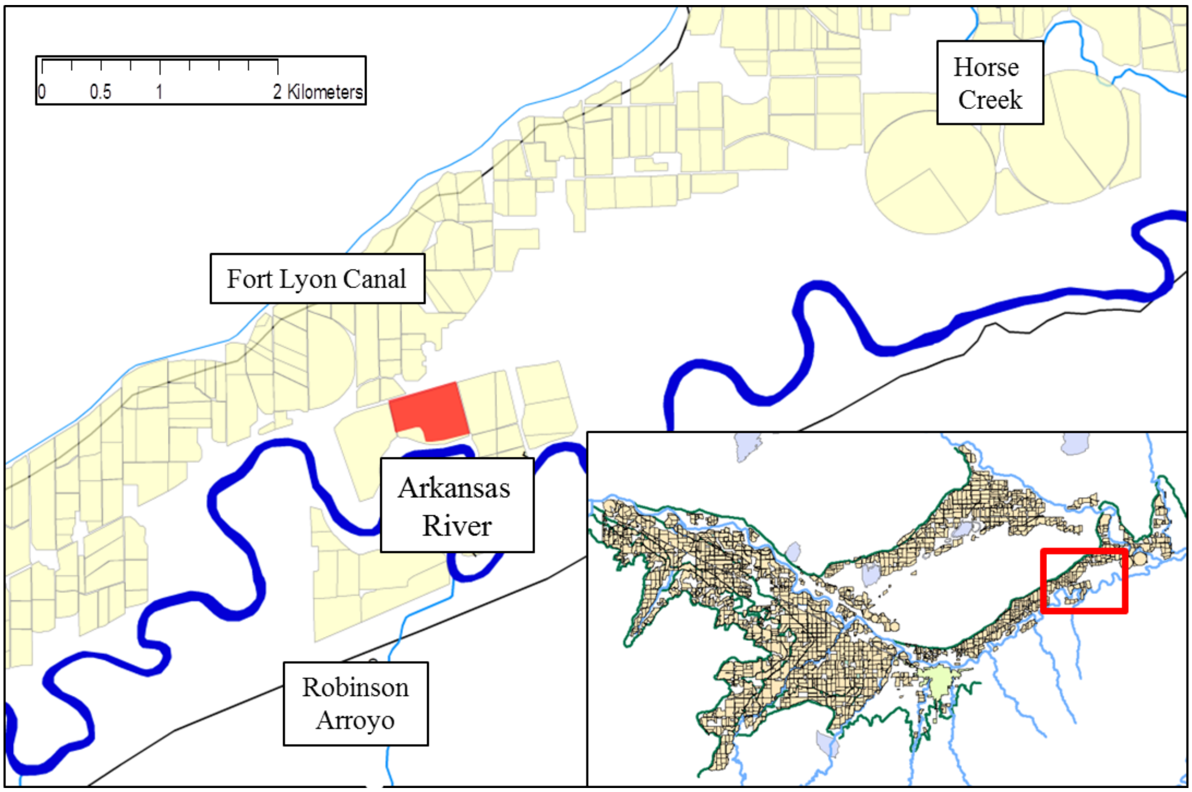


Figure 4.23. The location of Field 7 within the LARV.

Figure 4.24A shows that depletion to the Arkansas River is spread out spatially, but are largest at locations quite close to the stressed cell. The similarity in timing of initial depletion estimates is shown in Figure 4.24B, though the Glover-Balmer solution larger total depletion. Positive values are indicated in Figure 4.24 to indicate stream depletion due to water extraction. The magnitude of depletion predicted within the first months following the stress event by the MODFLOW-UZF model are significantly higher than that of the Glover-Balmer solution due to its ability to estimate more complex groundwater flow patterns and heterogeneities. Although initial stream depletion estimates from the MODFLOW-UZF model are higher initially, stream depletion is predicted to end more quickly. This results in an overestimation of stream depletion by the Glover-Balmer solution within the first year of simulation, as seen in Figure 4.24C.

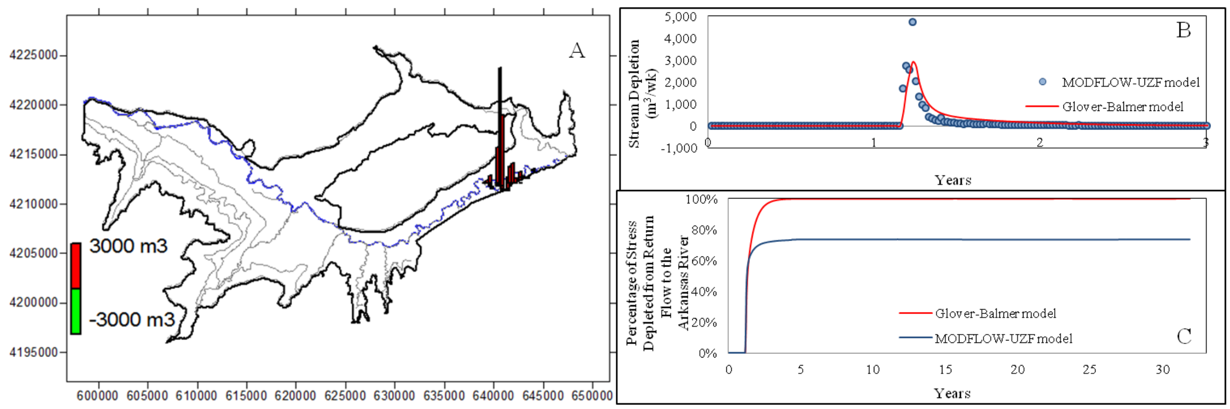


Figure 4.24. (A) Bar plot of stream depletion within the LARV for Field 7, (B) the amount of stream depletion occurring throughout the 32-year simulation period, as predicted by the Glover-Balmer solution and MODFLOW-UZF model, and (C) the cumulative depletion expressed as a percentage of the total stress volume.

MODFLOW-UZF model predicted water table elevation change for each grid cell in the shortest straight-line path between the Arkansas River and stressed grid cell is shown in Figure 4.25A. Negative values indicate a lowering of the water table compared to the baseline case, which is expected in water extraction scenarios. The MODFLOW-UZF grid cell residing about 500 m from the river experiences a larger change in water table elevation than the cell 250 m from the river. This is consistent with scenarios of lease-fallowing and water addition to the saturated zone, where larger water table elevation change occurs further from the Arkansas River. Changes in upflux to ET volumes, shown in Figure 4.25B, are calculated by subtracting the extraction scenario values from the baseline values. Therefore, positive values indicate a decrease in upflux to ET for the extraction scenarios. When the water table is lowered, the MODFLOW-UZF model assumes less water is available to plants from the saturated zone. During most extraction scenarios, the MODFLOW-UZF model predicts a decrease in ET from the saturated zone and an increase in ET from the unsaturated zone. This also is related to a lowering of the water table as plants must try to consume additional water from the unsaturated zone. Like plots similar to 4.25B for other scenarios, changes in upflux to ET extend beyond the areal extent of the stressed grid cell to surrounding grid cells, some of which reside under other fields in the MODFLOW-UZF model.

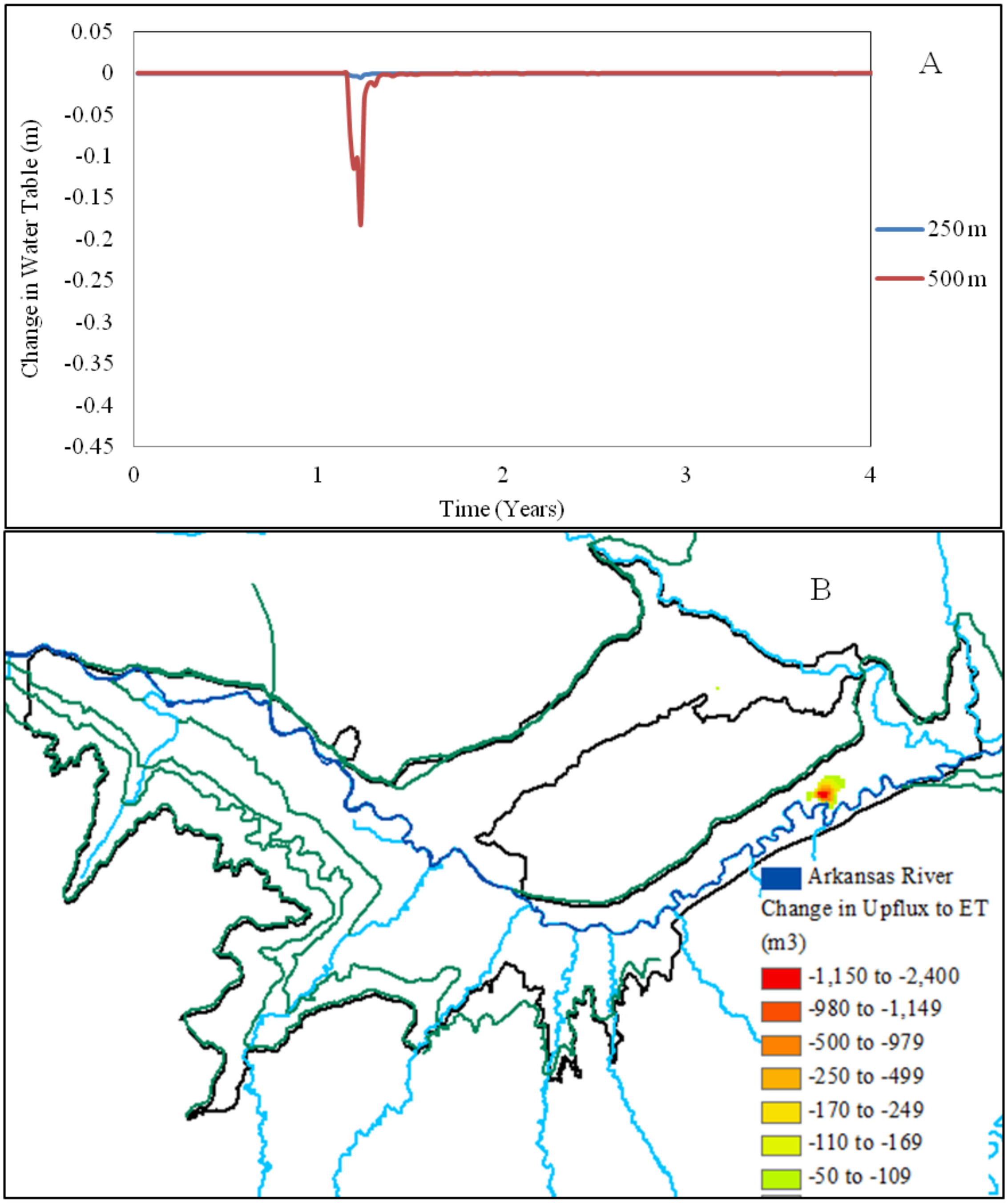


Figure 4.25. (A) The water table elevation change for MODFLOW-UZF model grid cells in the shortest straight-line path between the stressed cell and Arkansas River, and (B) the total change in upflux to ET for each grid cell for the 32-year simulation period.

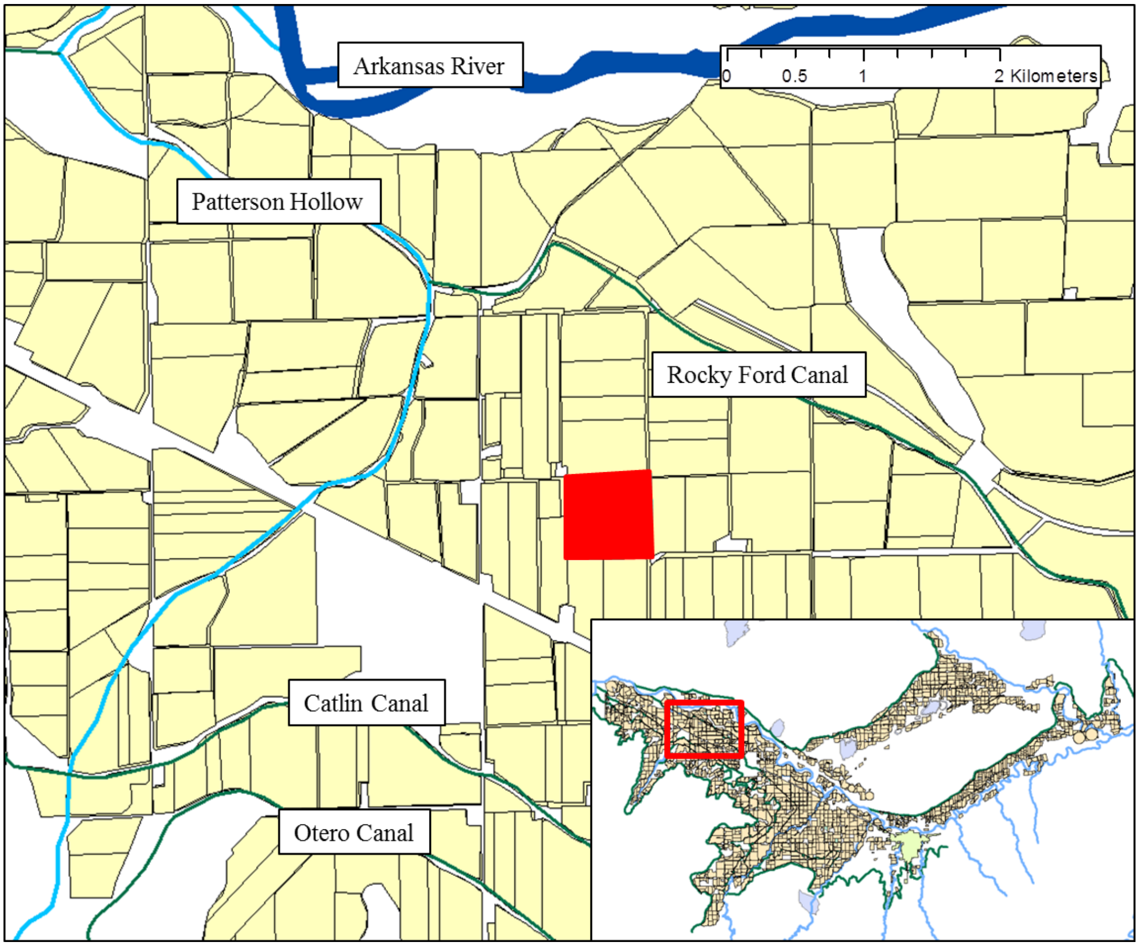


Figure 4.26. The location of Field 8 within the LARV.

Field 8 resides near Patterson Hollow about 2100 m from the main stem of the Arkansasa River. Figure 4.26 shows the specific location within the LARV. Due to the hydraulic conductivity patterns predicted by the MODFLOW-UZF model, a significant amount of stream depletion occurs at Patterson Hollow and the Rocky Ford Canal, as shown in Figure 4.27A. Figure 4.27B depicts the difference in timing of stream depletion to the Arkansas River estimated by the MODFLOW-UZF model and the Glover-Balmer solution. Depletion estimations by the Glover-Balmer solution lag by about two years compared to the MODFLOW-UZF model, and the Glover-Balmer solution also predicts a significantly longer residual effect that extends well beyond the effects seen using the MODFLOW-UZF model. The cumulative depletion predicted over time highlight the disparity between the two methods, as shown in Figure 4.27C.

Although tributary depletions are included in the MODFLOW-UZF estimations in Figure 4.27, changes in canal interactions are not. Therefore, changes in canal interactions do not appear in Figures 4.27B or 4.27C. That is one reason for the discrepancy between the Glover-Balmer solution and MODFLOW-UZF model stream depletion predictions, highlighted in Figure 4.27C. Other reasons include MODFLOW-UZF estimations of changes in aquifer storage, unsaturated zone ET, saturated zone ET, recharge to the water table, and infiltration. Figure 4.27 shows that discrepancies between the Glover-Balmer solution and MODFLOW-UZF model can be quite significant, and that the Glover-Balmer solution can predict much greater stream depletion.

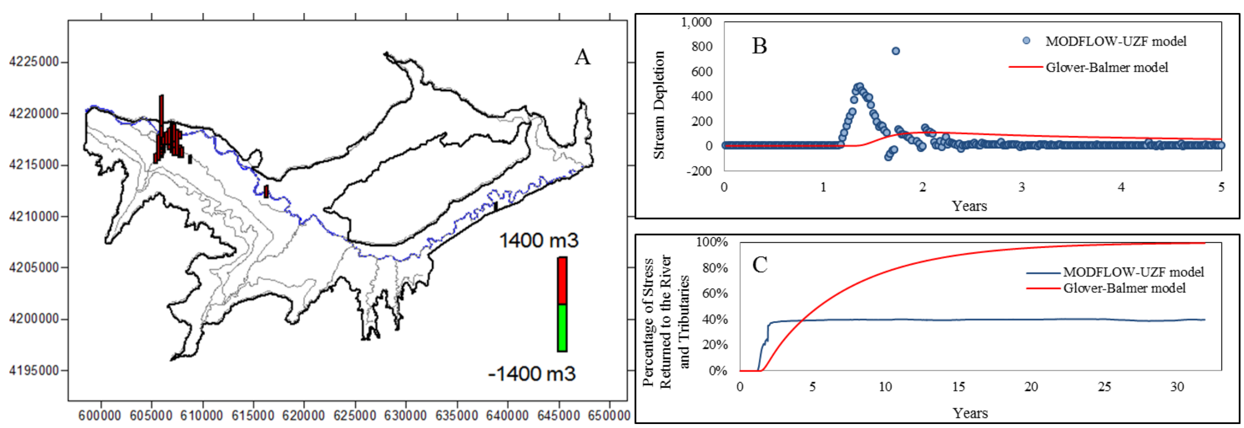
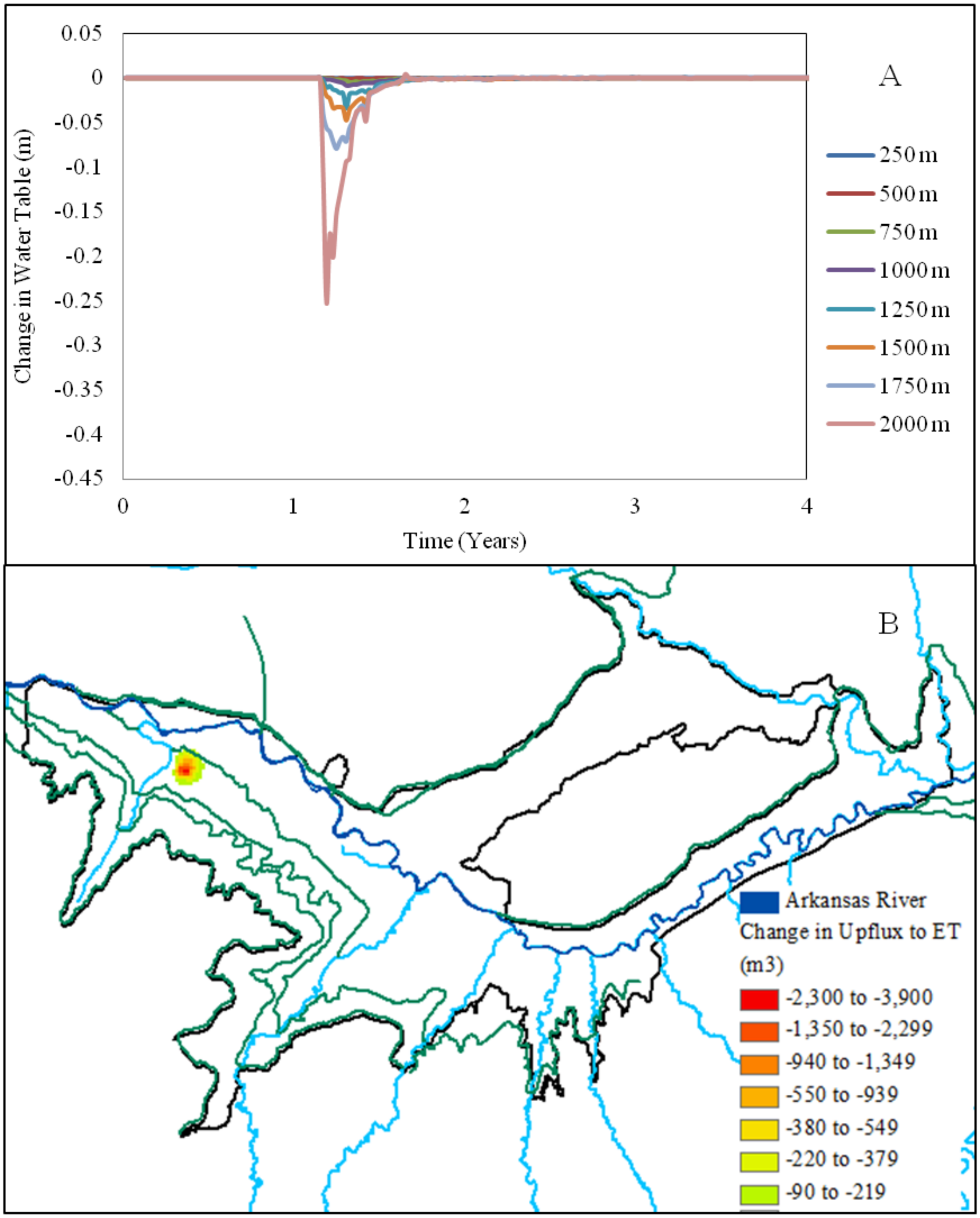


Figure 4.27. (A) Bar plot of stream depletion within the LARV for Field 7, (B) the amount of stream depletion occurring throughout the 32-year simulation period, as predicted by the Glover-Balmer solution and MODFLOW-UZF model, and (C) the cumulative depletion expressed as a percentage of the total stress volume.

A lowering of the water table in grid cells in the shortest straight-line path between the stressed cell and Arkansas River can be seen in Figure 4.28A. Similar to all other scenarios, the water table elevation change is largest in grid cells nearest the stressed cell (and furthest from the Arkansas River). All water table elevations shown in Figure 4.28A return to baseline levels within 6 – 8 months of the stress event. Figure 4.28B shows that upflux to ET decreases compared to the baseline case (indicated by positive values), and that many surrounding grid cells are also affected. The effects can also be seen near Patterson Hollow and the Rocky Ford Canal. This, along with Figure 4.27A, is an example of how altered field water management can affect tributaries and canals.



4.28. (A) The water table elevation change for grid cells in the shortest straight-line path between the stressed cell and Arkansas River, and (B) the total change in upflux to ET for each grid cell in the 32-year simulation period.

4.3.2. *Summary of scenarios with water extraction from the saturated zone*

Figure 4.29 shows the change in net ET for each extraction scenario. As water is extracted from the saturated zone, a depression in the water table is created, and it can be seen that net ET tends to decrease (indicated by negative values in Figure 4.29). In most extraction scenarios, the MODFLOW-UZF model predicts an increase in unsaturated zone ET and a decrease in ET from the saturated zone. This occurs because of the lowering of the water table, simultaneously increasing the size of the unsaturated zone and decreasing the availability of water in the saturated zone to plant roots. However, for extraction scenarios in which net ET increases (indicated by positive values in Figure 4.29), the increase in unsaturated zone ET is larger than the decrease in saturated zone ET. Such scenarios are exceptional; Figure 4.29 shows that net ET typically decreases by about 5 – 30%. This is opposite to what is seen in Figure 4.17 for scenarios of water addition to the saturated zone. There appears to be no trend relating the change in net ET to distance from the stream, suggesting that change in net ET due to extraction is mostly independent of distance from the main stem of the Arkansas River.

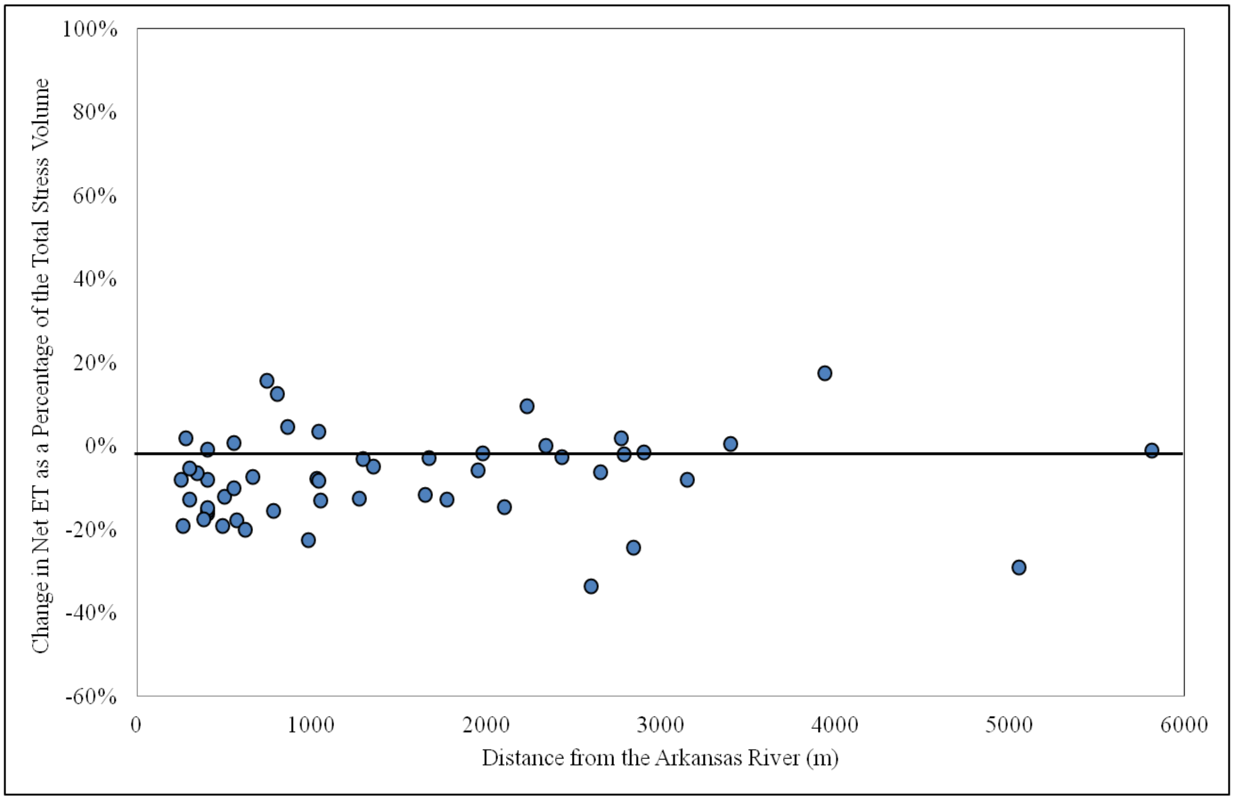


Figure 4.29. Change in groundwater storage predicted by the MODFLOW-UZF model as a percentage of the stress volume by water extraction versus distance from the Arkansas River.

Figure 4.30 shows that changes in canal interactions can be relatively variable depending on the proximity of the stressed grid cell to an irrigation canal. Following the notation shown previously in Figure 4.18, positive values correlate to an increase in canal seepage in the stress scenario. Figure 4.30 shows that canal seepage generally increases for water extraction scenarios. This is caused by a lowering of the water table around the extraction site, which creates a larger hydraulic gradient to deplete more water from canals. Though increased canal seepage tends to equate to less than about 40% of the total stress volume for most scenarios, in some cases volumes of increased canal seepage can be around 90% of the stress volume. In such cases, stream depletion estimates from the Glover-Balmer solution will drastically differ from the MODFLOW-UZF model because the Glover-Balmer solution does not consider the influence of irrigation canals. If it is assumed that irrigation canals do not influence stream depletion due to pumping, Figures 4.18 and 4.30 show that significant errors can arise.

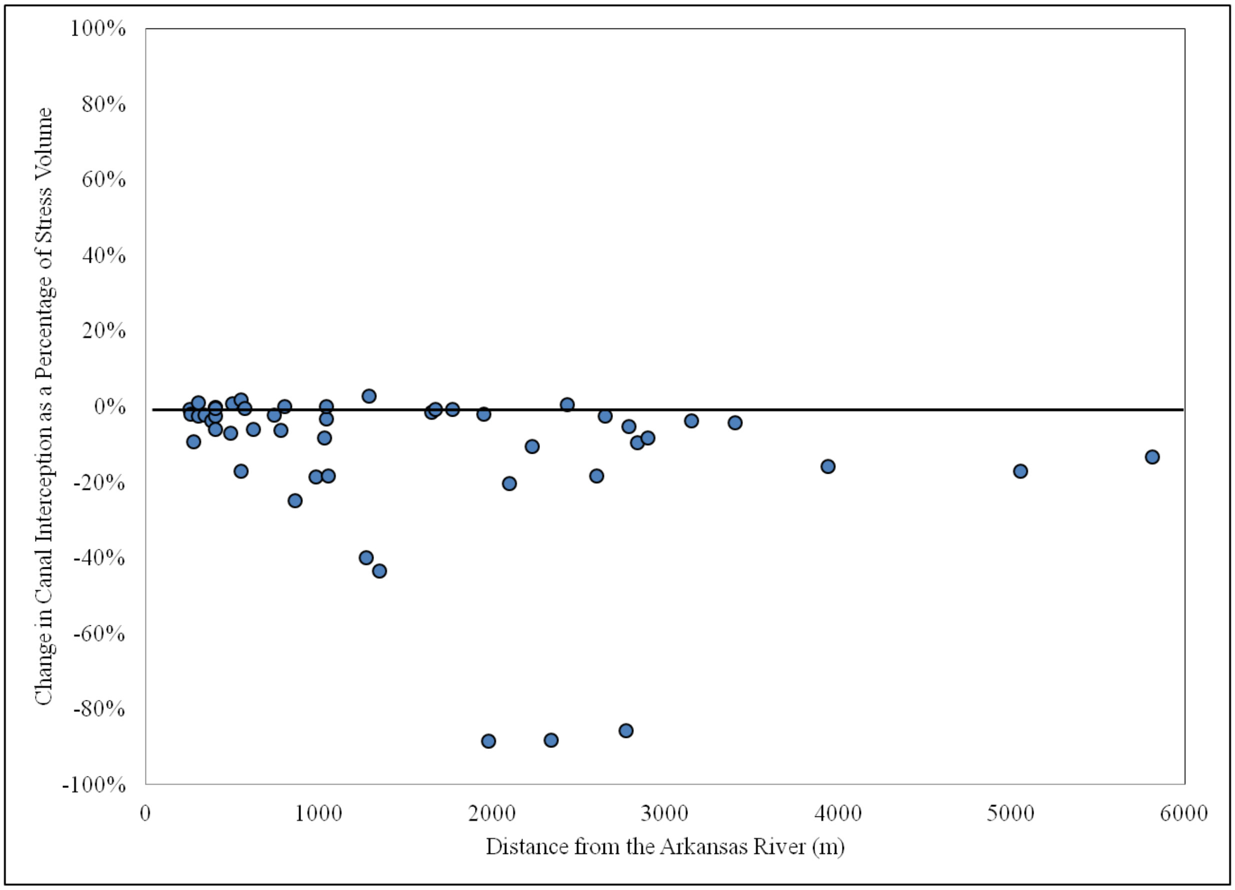


Figure 4.30. Change in canal interaction predicted by the MODFLOW-UZF model as a percentage of stress volume by water extraction versus distance to the Arkansas River.

Again, similar to the scenarios of water addition to the saturated zone (Figure 4.19), groundwater storage change varies considerably for extraction scenarios; the summary can be seen in Figure 4.31. Negative values indicate the total groundwater storage volume is smaller in the stressed case. This shows that additional water is leaving subsurface storage due to the stress event. Water extraction events tend to create a depression in the water table, and the depression can induce water from groundwater storage into other hydrologic features. Figure 4.31 shows that the groundwater storage change is highly variable and can be significantly large. Large groundwater storage change can lead to a significant difference in stream depletion estimates from the Glover-Balmer solution and MODFLOW-UZF model. The Glover-Balmer solution assumes all water pumped from an aquifer will eventually deplete from the stream. Positive percentages indicate an increase in groundwater storage compared to the baseline scenario. It is hypothesized that this is due to a regionally-scaled change in the hydraulic gradient such that water is induced into the subsurface but not consumed as ET or intercepted by the stream and canal networks. Though such cases are unusual, they show that changes in hydrologic features can be variable and counterintuitive.

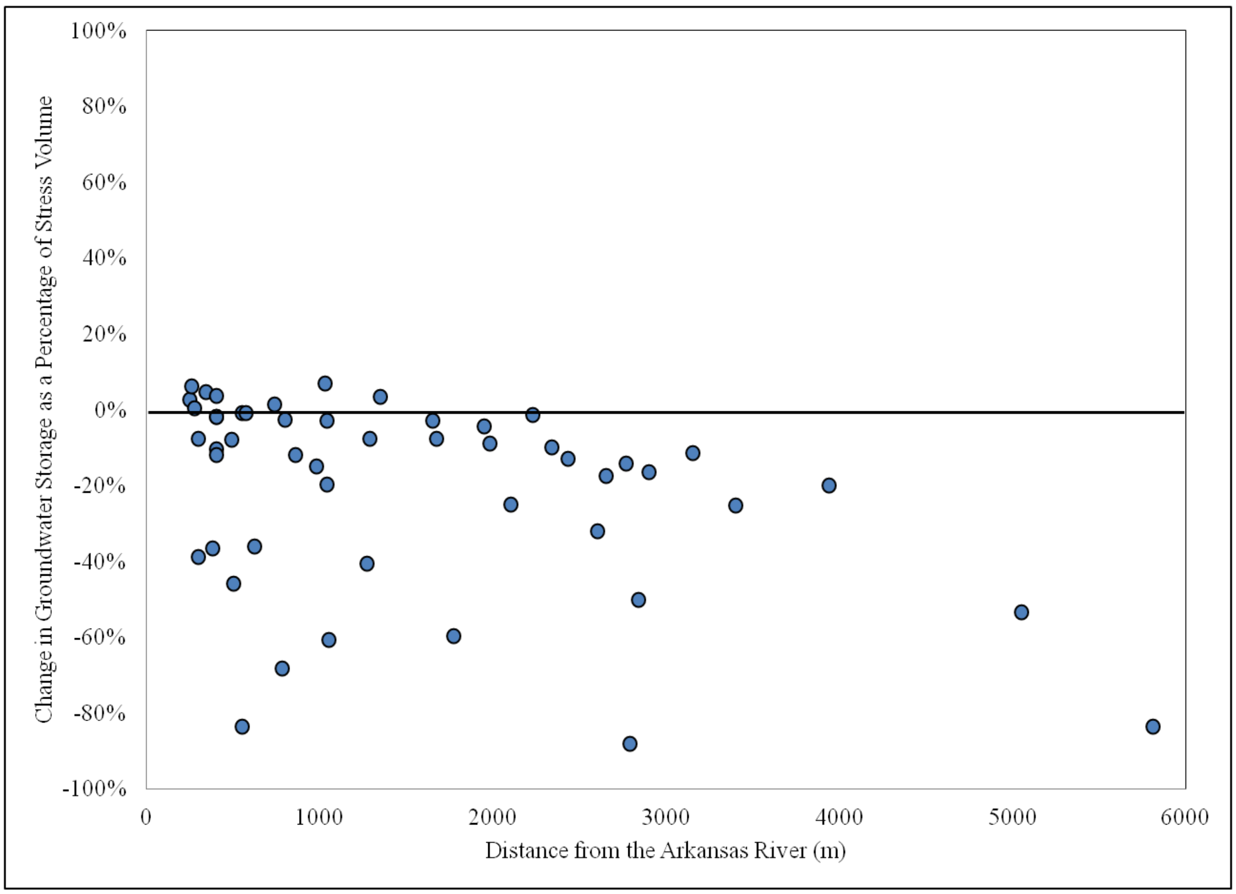


Figure 4.31. Change in groundwater storage predicted by the MODFLOW-UZF model as a percentage of the stress volume versus distance to the Arkansas River.

The ratios of total cumulative stream depletion expressed as a percentage of the total stress volume by the MODFLOW-UZF model and the Glover-Balmer solution are shown for each extraction scenario in Figure 4.32. Figure 4.32 shows that in almost all cases, the Glover-Balmer solution overestimates stream depletion compared to the MODFLOW-UZF model. This trend is consistent with the conclusions of other studies described in Chapter 2. Some discrepancies between predictions of stream depletion are relatively small. Many discrepancies, like scenarios where ratios are less than 0.6, for example, could be deemed significant. The trend of significant overestimation by the Glover-Balmer solution is consistent in results of water addition scenarios (saturated zone and ground surface addition), water extraction scenarios, and lease-fallowing examples. This creates an impetus to exercise caution when applying the Glover-Balmer solution in practice.

In a few cases, stream depletion predictions by the Glover-Balmer solution and MODFLOW-UZF model match relatively well. Though similar total cumulative depletion estimates can occur at relatively large distances from the river (greater than 1 km), they occur most frequently within about 0.5 – 1 km of the river. Under such circumstances, the majority of water extracted from the aquifer is then depleted from the stream network. This means that net ET, canal interaction, and groundwater storage change are largely unchanged, and simplifying assumptions made by the Glover-Balmer solution do not create significant discrepancies with the MODFLOW-UZF model predictions of stream depletion. As distance from the stream increases, confidence in the assumptions made by the Glover-Balmer solution diminish as there are more opportunities for complexities in the MODFLOW-UZF system to influence stream depletion estimates. Results show that such complexities (ET, irrigation canal interaction, groundwater storage change, aquifer heterogeneity) also can have a large influence on stream depletion predictions relatively close to the river.

Close proximity to an irrigation canal can cause a large increase in canal seepage predicted by the MODFLOW-UZF model, meaning that little depletion occurs at the stream network. Although increased canal seepage is fairly predictable based on proximity to an irrigation canal, the magnitude of groundwater storage change and net ET change are difficult to predict. Groundwater storage and changes in net ET can also account for significant portions of the extracted volume. Since canal interaction, ET, and groundwater storage change are not considered by the Glover-Balmer solution, the Glover-Balmer solution overestimates stream depletion compared to the MODFLOW-UZF model in the majority of extraction scenarios.

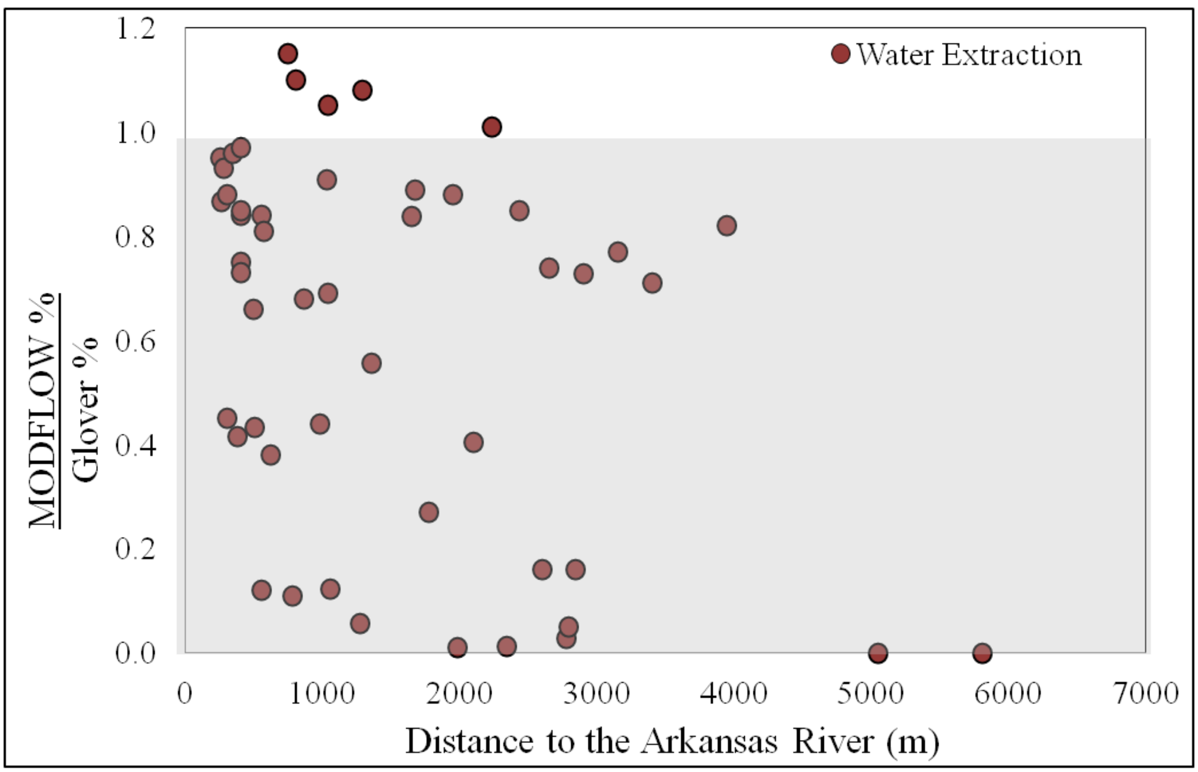


Figure 4.32. The ratio of the cumulative volume of stream depletion as a percentage of the stress volume predicted by the MODFLOW-UZF model divided by the cumulative volume of accretion as a percentage of the stress volume predicted by the Glover-Balmer method at the end of the 32-

year simulation for 52 scenarios of water extraction from the saturated zone versus distance from the Arkansas River.

Table 4.2 shows the percentage of water extraction scenarios in which stream depletion estimates from the Glover-Balmer solution match those by the MODFLOW-UZF model relatively well. The Glover-Balmer solution tends to predict similarly to the MODFLOW-UZF model less well as distance from the Arkansas River increases. Stream depletion estimates are within 20% of each other in half of the scenarios within 1 km of the Arkansas River, and in less than half of those within 2 or 4 km. Similar to results from scenarios of water addition to the saturated zone (Table 4.1), Table 4.2 shows that the likelihood of the Glover-Balmer solution providing stream depletion estimates similar to those of the MODFLOW-UZF model decreases as distance from the Arkansas River increases.

Table 4.2. The percentage of scenarios in which estimates of stream depletion estimates by the Glover-Balmer solution are within 20% of those of the calibrated MODFLOW-UZF model in relation to shortest straight-line distance from the Arkansas River.

Straight-line distance to the Arkansas River (km)	Percentage of scenarios in which $0.8 \leq$ MODFLOW% / Glover-Balmer% ≤ 1.2
≤ 0.5	50
≤ 1.0	50
≤ 2.0	48
≤ 4.0	41

The time at which overestimation of stream depletion by the Glover-Balmer solution occurs is computed for each extraction scenario and is shown in Figure 4.33. Lines showing an overestimation of 10% and 20% are displayed. The percentage of scenarios in which overestimation occurs is plotted against time to show the trend throughout the 32-year simulation period. Overestimation occurs more quickly for water extraction scenarios compared to scenarios water addition to the saturated zone. Figure 4.33 shows that within about two years, at least 10% overestimation by the Glover-Balmer solution occurs in about half of the extraction scenarios, and within about 6 years, the Glover-Balmer solution is overestimating stream depletion by at least 10% in about 70% of scenarios of water extraction to the saturated zone. Overestimation of at least 20% occurs in about half of the extraction scenarios by about the seventh year of simulation. And similar to Figure 4.21, overestimation by the Glover-Balmer solution occurs in about half of the scenarios by the end of the 32-year simulation period.

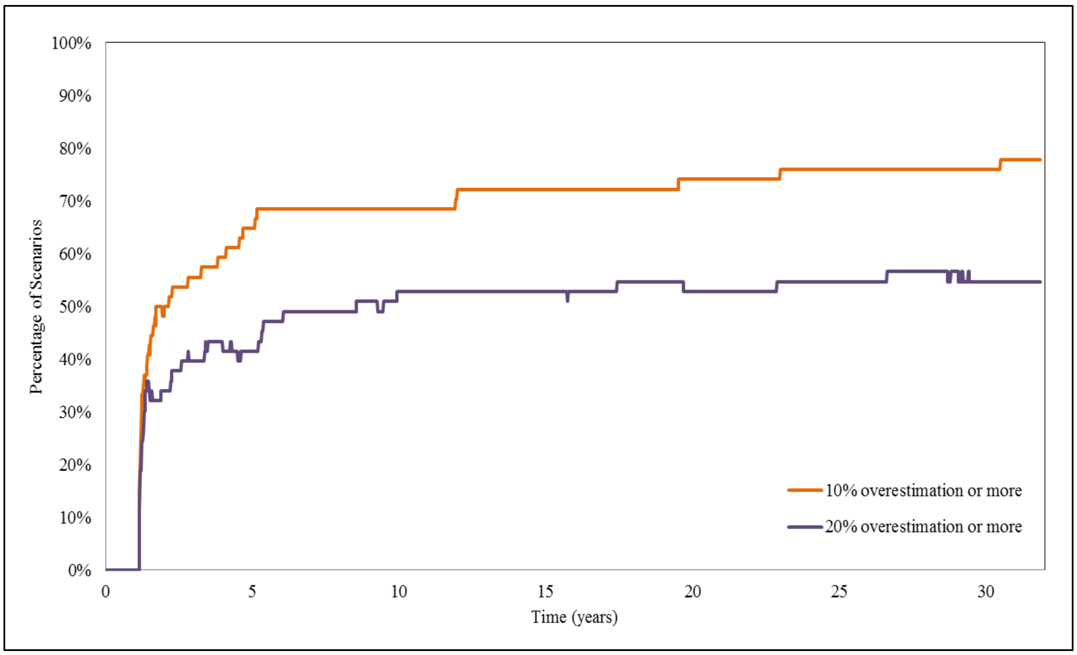


Figure 4.33. Percentage of scenarios in which the Glover-Balmer model overestimates stream depletion in comparison to predictions by the calibrated MODFLOW-UZF model by at least 10% or 20% for water extraction scenarios.

SUMMARY, CONCLUSIONS, AND IMPLICATIONS

This thesis presents the methodology and results of a study of comparisons of the Glover-Balmer solution to a calibrated MODFLOW-UZF model application for the LARV in southeastern Colorado. Different scenario types are created to mimic real-world applications of the Glover-Balmer solution and compare predictions of stream depletion/accretion with those of the MODFLOW-UZF model. The results from four different scenario types are presented: lease-fallowing, water addition to the saturated zone, water addition to the ground surface, and water extraction from the saturated zone. For each scenario type, the same stresses (fallowing, water addition, or water extraction) are applied to both the Glover-Balmer solution and MODFLOW-UZF model. Aquifer parameter values are supplied to the Glover-Balmer solution from the set of calibrated values for the MODFLOW-UZF model. Estimates of stream depletion/accretion due to the stress event are obtained for the Glover-Balmer solution and MODFLOW-UZF model and are tabulated for the entire 32-year simulation period. Stream depletion/accretion estimates from both methods can then be compared. Although the Glover-Balmer solution only estimates stream depletion or accretion, additional results from the MODFLOW-UZF model such as changes in water table elevation, upflux, and other hydrologic components (i.e. canal interception, net ET, and groundwater storage) are presented and discussed. Such considerations lead to an understanding of discrepancies in stream depletion/accretion estimates between the Glover-Balmer and MODFLOW-UZF model.

5.1. Comparison of the Glover-Balmer solution with a calibrated MODFLOW-UZF model

Comparison of estimated cumulative depletion/accretion volume to Colorado's Lower Arkansas River and tributaries by the Glover-Balmer solution and a calibrated MODFLOW-UZF model revealed high variability in the comparative accuracy of the Glover-Balmer solution. The Glover-Balmer solution typically predicts depletion/accretion to the stream network substantially greater than that predicted by the MODFLOW-UZF numerical model. This finding is consistent with studies by Spalding and Khaleel (1991), Sophocleous et al. (1995), and others, which considered only cases of water extraction in hypothetical aquifer systems. However, results from some scenarios show that the simpler Glover-Balmer solution can yield estimated stream depletion/accretion volumes which are quite comparable to those simulated by the more complex MODFLOW-UZF model under certain circumstances. These circumstances entail application to areas where the change in net ET, groundwater storage, and influence from features such as irrigation canals are relatively small. They also tend to occur for locations relatively close to the main stem of the river; within about 0.5 to 1 km.

Results show that modeled changes in net ET, irrigation canal interaction, and groundwater storage can cause the MODFLOW-UZF model to predict stream accretion/depletion patterns and volumes significantly different than those of the Glover-Balmer solution. The MODFLOW-UZF model shows that as the water management regime for a field is changed, water extracted from or added to the field can influence net ET, canal interaction, or groundwater storage change such that stream depletion/accretion impacts are less drastic than those predicted by the simpler Glover-Balmer solution. It also is shown that the altered field water management practices can significantly influence the hydrologic features of neighboring fields, creating complex (and often compounding) regional changes in ET, water table elevation, and other related groundwater/surface water processes.

Although the Glover-Balmer solution can provide acceptable estimates under certain circumstances, this study demonstrates that the inability to adequately account for the complexity and heterogeneity of real-world irrigated stream-aquifer systems may render simplified analytical solutions quite unreliable. In applying the Glover-Balmer solution to estimate stream depletion/accretion in practice, these results stress the importance of access to data with which to better account for the complexity of real-world systems, and of accounting for processes such as ET, upflux to ET, groundwater storage change, and infiltration, which can markedly affect depletion/accretion patterns, especially as distance from the stream is increased.

5.2. Considerations in applying the Glover-Balmer solution

The simplifying assumptions under which the Glover-Balmer solution was developed must always be kept in mind when applying it to an actual stream-aquifer system. A comparative assessment of the Glover-Balmer solution in estimating stream depletion/accretion in the LARV in response to altered field water management has led to the following additional suggested considerations:

(1) In using the Glover-Balmer solution to estimate river depletion/accretion in irrigated stream-aquifer systems similar to the LARV, it may not be appropriate to use the Glover-Balmer solution at distances greater than 0.5 – 1 km. Good comparisons of results obtained from the MODFLOW-UZF model are rare at distances greater than these, and only occur in about half of the cases within these distances;

(2) The Glover-Balmer solution may need to be amended to consider the presence of hydrologic components that intercept or contribute to groundwater flow, as these may alter stream depletion/accretion in response to a stress event. This could mean assuming stream depletion/accretion occurs to the nearest tributary or irrigation canal, or assuming depletion/accretion to multiple stream components or irrigation canals. If stream depletion/accretion is assumed to occur at multiple locations, a criteria would be required to apportion depletion/accretion volumes to each stream or canal component;

(3) Since the Glover-Balmer solution is used to assess extractions from and additions to the saturated zone, the effects of unsaturated flow and storage processes on the timing and amount of stream depletions and accretions are not accounted for in the analysis but might be significant in some cases. Methods should be applied to estimate changes to unsaturated zone components such as ET and recharge to the saturated zone to determine how this may influence stream depletion/accretion;

(4) Heterogeneity of aquifer properties can cause depletion/accretion to occur more quickly or slowly than would be predicted using average aquifer parameter values. Although this study did not directly address this issue, it is inherent in the presented scenarios comparing the MODFLOW-UZF model and Glover-Balmer solution. It may be useful to consult additional lithological data and consider individual parameter data to create a quicker or slower response in depletion/accretion estimation from the Glover-Balmer solution. The consideration of numerous parameter value estimates encompassing a relatively large areal extent can help understand spatial parameter patterns that can influence groundwater flow; and

(5) Depletion/accretion can occur to several stream network components, and may not occur predominantly at the stream location nearest the field. Data on regional hydraulic head patterns in the aquifer can assist in predicting the location of depletion/accretion to the stream network. If numerical models are not available for use, methods can be created to modify the Glover-Balmer solution to estimate depletion/accretion to multiple locations.

5.3. Future studies

Although some lease-fallow scenarios were simulated, additional scenarios in a variety of locations within the LARV could provide additional insight regarding the efficacy of the Glover-Balmer solution for situations that closely resemble lease-fallowing. Similarly, scenarios involving the simultaneous fallowing of numerous fields throughout the LARV could reveal how the fallowing of fields within various proximities of each other interact to change hydrologic conditions. The stress volume applied in the extraction/addition scenarios in this study are relatively small in comparison to the total volumes pertaining to hydrologic features at a regional scale in the MODFLOW-UZF model. The stress volumes could be increased to a size the is deemed comparable to the volumes of regional hydrologic features. Additionally, the concurrent fallowing or stressing of multiple fields would consider a likely scenario in the LARV, and could explore the cumulative changes to hydrologic features.

It may be possible to retain the simplicity and ease-of-use commonly associated with analytical solutions by developing URFs from the MODFLOW-UZF model. A URF could be created for a specified area, and a set of different URFs could be created for the entire study region. This would allow someone to select the URF related to their study site, and quickly make estimations of stream depletion that are based on the MODFLOW-UZF model. Considerable effort would be required to determine the nature of the URFs derived from the MODFLOW-UZF model, with special attention given to complications due to the transient and non-linear calculations made by the model. As a means to allow the Glover-Balmer solution to estimate depletion/accretion to a stream, tributary, or irrigation canal simultaneously, techniques for developing methods to proportion depletion/accretion to multiple stream boundaries could be developed.

This study creates comparisons where all complexities within the MODFLOW-UZF model are considered. Comparisons could be made to isolate specific hydrologic features within the MODFLOW-UZF model (e.g. canal interception, tributary interception, groundwater storage, unsaturated zone processes) to determine their individual potential impacts on stream depletion/accretion estimates. This would be more similar to the study by Sophocleous et al. (1995), and could guide practical applications of the Glover-Balmer solution.

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APPENDIX A: DETAILED RESULTS FROM THE MODFLOW-UZF MODEL FOR SCENARIOS OF WATER EXTRACTION/ADDITION TO THE SATURATED ZONE

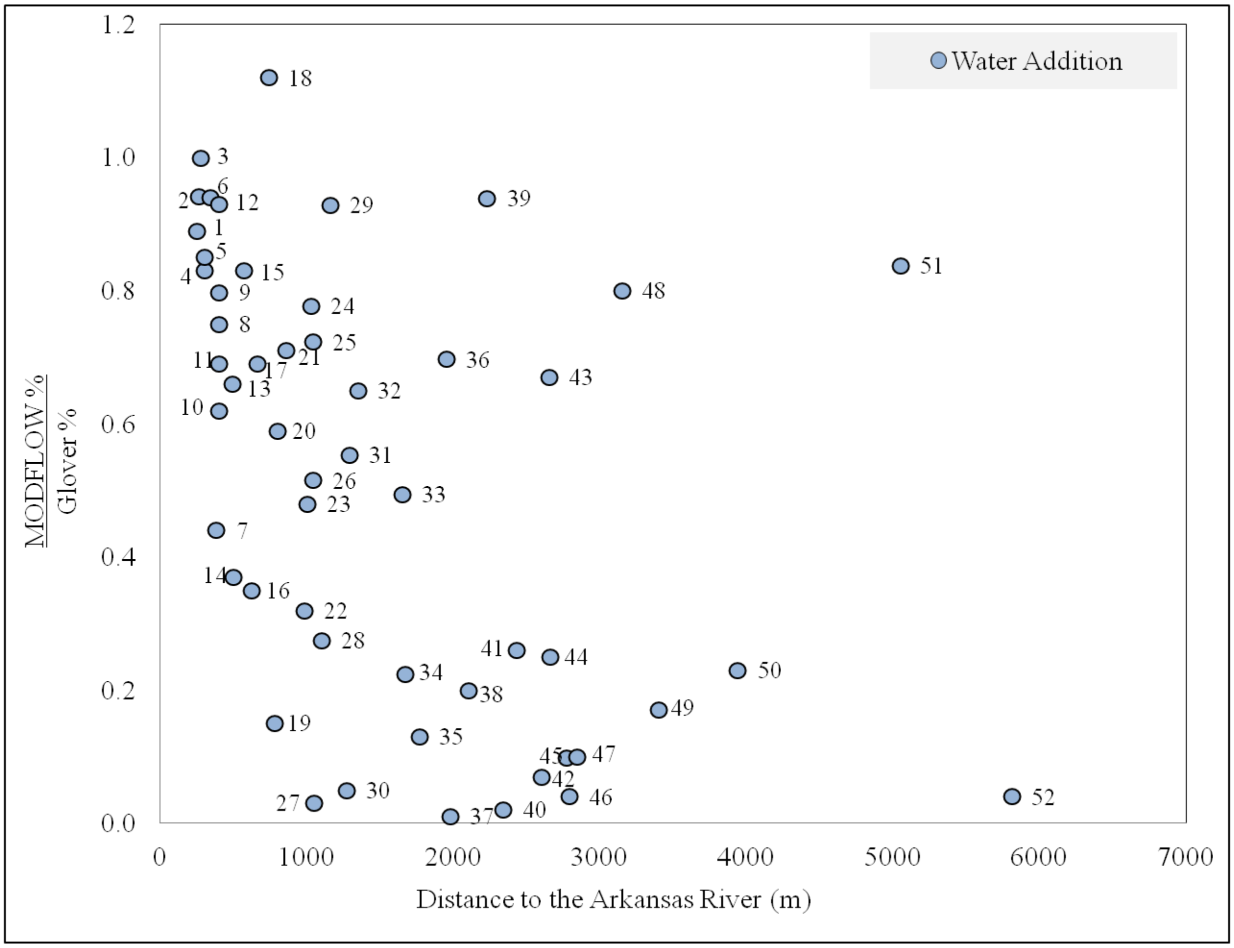

Figure A.1. The ratio of the cumulative volume of stream accretion as a percentage of the stress volume predicted by the MODFLOW-UZF model divided by the cumulative volume of accretion as a percentage of the stress volume predicted by the Glover-Balmer method at the end of the 32-year simulation for 52 scenarios of water addition to the saturated zone versus distance from the Arkansas River, with data labels of exact distances for reference in the following detailed tables.

Table A.1. Differences in individual hydrologic features as estimated by the MODFLOW-UZF model for each scenario of water addition to the saturated zone.

Scenarios of Water Addition to the Saturated Zone						
Individual MODFLOW-UZF Components						
All Values Expressed as (Baseline Scenario - Stress Scenario)						
Total Stress Volume = 30,861 m^3						
Scenario #	Straight-Line Distance to River (m)	Recharge (m^3)	Infiltration (m^3)	Unsaturated Zone ET (m^3)	Saturated Zone ET (m^3)	Net ET (Unsat. + Sat.) (m^3)
1	250	-5,578.2	2,348.3	4,440.5	-7,508.5	-3,067.9
2	260	-16,857.9	-1,435.3	19,865.5	-25,166.6	-5,301.1
3	275	655.2	5,932.2	4,222.2	-2,643.0	1,579.2
4	300	-9,725.8	-890.4	6,936.9	-6,448.4	488.5
5	300	-7,295.5	-2,375.3	7,681.9	-10,957.0	-3,275.2
6	340	-19,235.9	-3,422.9	11,121.4	-13,776.7	-2,655.3
7	380	-2,560.3	3,235.1	7,912.0	-14,528.2	-6,616.1
8	400	-14,035.9	-7,577.8	4,291.9	-5,628.0	-1,336.1
9	400	-9,019.4	-5,880.2	9,616.1	-13,478.7	-3,862.5
10	400	-17,964.7	-7,185.9	9,692.5	-15,154.4	-5,461.8
11	400	-10,111.5	2,485.0	11,498.1	-17,519.7	-6,021.6
12	400	-2,813.9	5,050.0	7,828.4	-9,933.7	-2,105.3
13	490	-11,804.2	5,317.8	10,779.6	-17,171.2	-6,391.6
14	500	935.9	11,619.9	5,832.8	-9,684.3	-3,851.5
15	570	-16,365	-4,169.4	12,603.5	-18,309.5	-5,706.0
16	620	-1,554.0	837.4	5,082.8	-10,821.6	-5,738.8
17	660	-7,320.1	549.7	9,588.0	-12,343.2	-2,755.2
18	740	-26,959.3	-2,400.8	23,405.6	-20,572.6	2,833.0
19	780	5,872.0	11,004.0	6,241.7	-9,962.1	-3,720.5
20	800	-23,671.1	3,462.4	19,832.3	-17,669.9	2,162.4
21	860	-29,732.9	5,989.1	36,661.1	-34,783.4	1,877.6
22	980	-2,972.6	5,982.0	9,606.3	-14,407.3	-4,800.9
23	1000	-8,314.2	-5,326.7	1,955.9	-2,880.1	-924.2
24	1030	-14,654.0	-841.2	13,177.3	-17,366.9	-4,189.6
25	1040	-21,252.9	2,289.0	19,322.8	-22,802.2	-3,479.4
26	1040	-22,814.6	-4,659.2	16,629.2	-14,808.2	1,821.1
27	1050	-1,981.4	8,692.8	5,369.7	-9,878.2	-4,508.6

28	1100	-12,791.9	-6,524.6	6,494.6	-7,785.0	-1,290.3
29	1160	-12,218.1	-460.5	14,475.6	-17,247.3	-2,771.7
30	1270	-8,555.2	2,890.8	8,691.7	-13,347.8	-4,656.1
31	1290	-7,461.8	1,282.1	10,474.1	-12,759.2	-2,285.1
32	1350	-19,597.7	-4,283.8	15,221.59	-15,905.2	-683.6
33	1650	-12,097.9	2,071.8	12,146.2	-16,464.9	-4,318.8
34	1670	-10,791.6	-6,145.1	7,981.2	-9,632.7	-1,651.6
35	1770	-16,589.9	9,792.7	30,257.3	-32,913.1	-2,655.8
36	1950	-4,400.5	-3,744.1	8,751.4	-10,429.6	-1,678.3
37	1980	-4,464.6	-176.4	6,016.9	-5,829.2	187.7
38	2100	-16,076.6	-2,777.0	15,987.49	-19,961.6	-3,974.1
39	2230	-32,145.9	-8,059.6	24,941.3	-20,158.8	4,782.5
40	2340	-11,278.6	180.2	6,264.2	-5,793.6	470.6
41	2430	-1.0E+04	-838.2	1.2E+04	-1.4E+04	-2,205.4
42	2600	2,573.6	11,748.3	12,653.1	-19,602.2	-6,949.1
43	2650	-8,779.0	292.8	15,005.9	-16,798.8	-1,792.8
44	2660	-14,084.0	-6,498.0	10,342.8	-12,001.2	-1,658.4
45	2770	-16,934.8	-67.6	10,218.4	-8,841.3	1,377.0
46	2790	-5,307.6	-232.8	9,469.1	-9,522.2	-53.1
47	2840	6,588.6	9,624.2	11,163.4	-16,772.4	-5,609.0
48	3150	-14,449.6	-6,376.3	13,087.1	-15,930.2	-2,843.1
49	3400	-23,321.0	3,223.1	19,526.1	-20,852.9	-1,326.8
50	3940	-39,123.4	-3,730.6	35,675.4	-29,026.8	6,648.6
51	5050	-20,685.7	-4,028.7	16,423.0	-26,651.0	-10,227.9
52	5810	-31,610.6	3,038.7	29,417.3	-32,463.0	-3,045.7

Table A.2. Differences in individual hydrologic features as estimated by the MODFLOW-UZF model for each scenario of water addition to the saturated zone.

Scenarios of Water Addition to the Saturated Zone						
Individual MODFLOW-UZF Components						
All Values Expressed as (Baseline Scenario - Stress Scenario)						
Total Stress Volume = 30,861 m^3						
Scenario #	Canal Seepage (m^3)	MODFLOW Accretion (m^3)	MODFLOW/Glover ratio	Change in Groundwater Storage (% of stress volume)	Avg. T (m^2/wk)	Avg. S_y
1	-250.0	28,524.0	0.89	-0.18	3078	0.269
2	105.0	27,300.0	0.94	-0.29	2957	0.158
3	-2,695.0	30,818.0	1.00	-0.04	2754	0.171
4	-4,716.0	25,676.0	0.83	-0.31	2754	0.171
5	-383.0	26,921.0	0.85	-0.25	4632	0.245
6	-219.0	30,521.0	0.94	-0.09	7100	0.243
7	-977.0	13,692.0	0.44	-0.81	3881	0.23
8	-38.0	23,137.0	0.75	-0.29	6322	0.141
9	-139.0	27,019.0	0.80	-0.25	4302	0.179
10	346.0	21,483.0	0.62	-0.47	6352	0.237
11	-701.0	22,978.0	0.69	-0.47	5980	0.234
12	-344.0	30,302.0	0.93	-0.10	4296	0.233
13	-1,765.0	20,470.0	0.66	-0.49	4379	0.138
14	403.0	11,528.0	0.37	-0.74	6086	0.228
15	-263.0	25,535.0	0.83	-0.35	1601	0.141
16	-1,787.0	11,521.0	0.35	-0.76	7124	0.169
17	226.0	28,387.0	0.69	-0.18	6717	0.238
18	-469.0	34,586.0	1.12	0.20	2458	0.243
19	-1,686.0	1,322.0	0.15	-1.14	4110	0.219
20	-568.0	33,084.0	0.59	0.12	4150	0.23
21	-6,840.0	21,913.0	0.71	-0.45	3446	0.336
22	-4,137.0	9,730.0	0.32	-0.70	6711	0.137
23	167.0	30,284.0	0.48	-0.06	4731	0.153
24	-107.0	27,949.0	0.78	-0.22	6086	0.228
25	-837.0	21,465.0	0.72	-0.44	8164	0.246
26	286.0	32,796.0	0.52	0.13	3843	0.228
27	-5,104.0	1,875.0	0.03	-1.25	4662	0.226

28	420.0	28,906.0	0.28	-0.12	4241	0.179
29	-187.0	27,156.0	0.93	-0.20	4608	0.235
30	-11,614.0	1,429.0	0.05	-1.48	4657	0.222
31	-521.0	29,509.0	0.55	-0.13	3205	0.224
32	-12,947.0	20,081.0	0.65	0.05	3287	0.144
33	-1,488.0	26,397.0	0.49	-0.23	3795	0.222
34	-75.0	28,179.0	0.22	-0.14	4313	0.181
35	1,449.0	8,621.0	0.13	-0.76	3524	0.208
36	272.0	27,179.0	0.70	-0.18	4334	0.179
37	-28,638.0	250.0	0.01	-1.91	4127	0.198
38	-3,729.0	6,228.0	0.20	-0.81	2404	0.144
39	-3,339.0	33,616.0	0.94	0.35	2964	0.214
40	-26,999.0	4.0	0.02	-1.84	3638	0.189
41	-143.0	26,145.0	0.26	-0.23	4112	0.177
42	-2,573.0	2,059.0	0.07	-1.07	3267	0.147
43	-401.0	20,680.0	0.67	-0.40	2715	0.196
44	152.0	25,981.0	0.25	-0.21	3966	0.177
45	-29,012.0	456.0	0.10	-1.88	2708	0.174
46	-21,894.0	1,256.0	0.04	-0.25	8697	0.198
47	-1,323.0	2,896.0	0.10	-1.04	1600	0.148
48	-327.0	24,605.0	0.80	-0.28	3674	0.176
49	-1,985.0	22,348.0	0.17	-0.26	2681	0.193
50	-4,432.0	26,736.0	0.23	0.23	2357	0.19
51	-5,096.0	17,577.0	0.84	-0.60	1566	0.16
52	-15,368.0	1,516.0	0.04	-1.55	2638	0.196

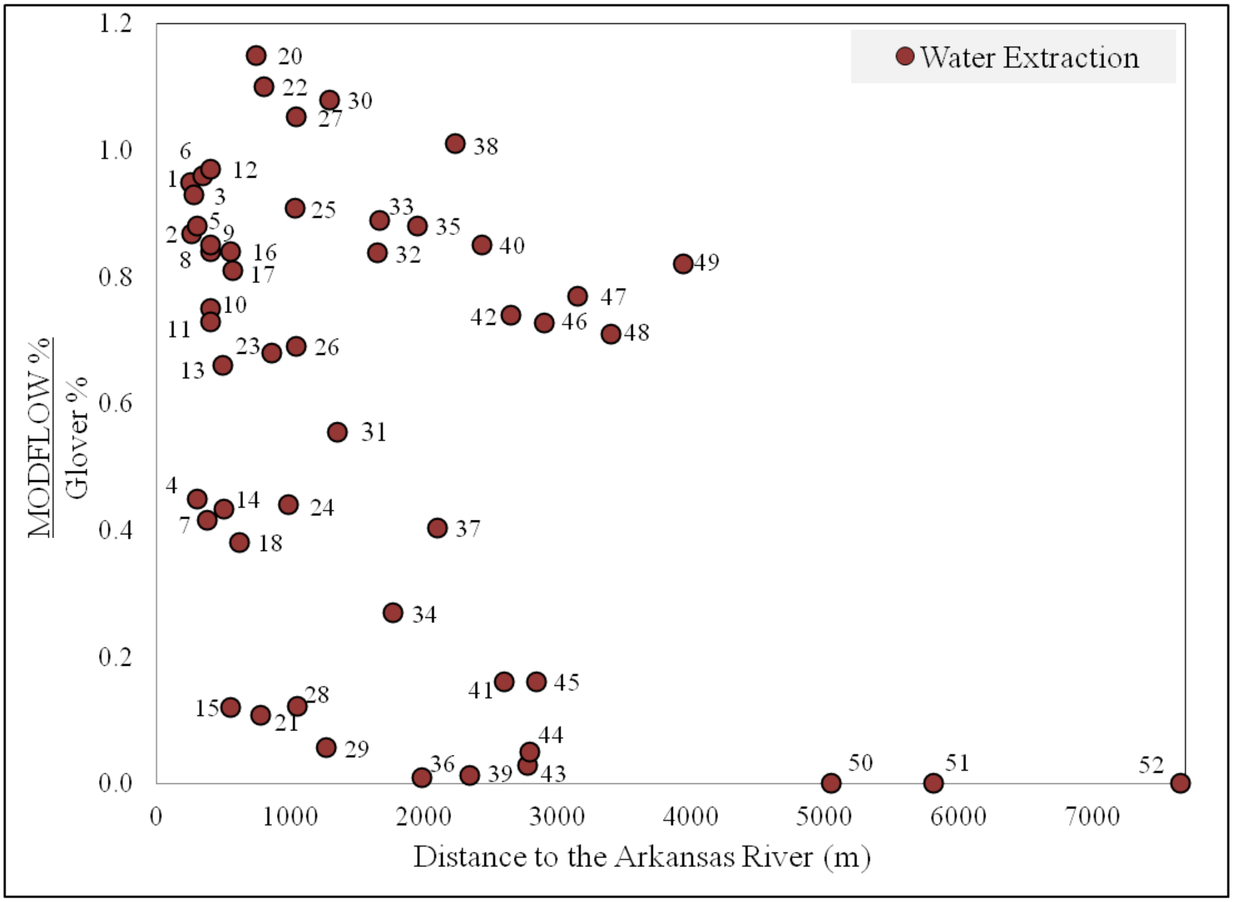

Figure A.2. The ratio of the cumulative volume of stream depletion as a percentage of the stress volume predicted by the MODFLOW-UZF model divided by the cumulative volume of depletion as a percentage of the stress volume predicted by the Glover-Balmer method at the end of the 32-year simulation for 52 scenarios of water extraction from the saturated zone versus distance from the Arkansas River, with data labels of exact distances for reference in the following detailed tables.

Table A.3. Differences in individual hydrologic features as estimated by the MODFLOW-UZF model for each scenario of water extraction from the saturated zone.

Scenarios of Water Extraction from the Saturated Zone						
Individual MODFLOW-UZF Components						
All Values Expressed as (Baseline Scenario - Stress Scenario)						
Total Stress Volume = 30,861 m^3						
Scenario #	Straight-Line Distance to River (m)	Recharge (m^3)	Infiltration (m^3)	Unsaturated Zone ET (m^3)	Saturated Zone ET (m^3)	Net ET (Unsat. + Sat.) (m^3)
1	250	-9,806.3	-6,976.2	-2,383.2	4,876.0	2,492.8
2	260	12,496.9	-2,177.6	-14,627.8	20,561.1	5,933.3
3	275	8,253.9	-635.25	-3,539.6	2,947.4	-592.2
4	300	-3,331.9	-14,620.5	-7,631.5	11,563.7	3,932.3
5	300	-2,128.9	-9,785.3	-4,551.4	6,221.5	1,670.2
6	340	6,941.3	-4,141.0	-9,303.9	11,285.9	1,982.0
7	380	-2,380.2	-10,393.6	-6,727.1	12,174.4	5,447.4
8	400	3,014.0	-6,305.6	-5,098.1	7,590.1	2,492.0
9	400	3,299.9	-5,471.4	-8,193.5	13,221.6	5,028.2
10	400	7,454.6	-4,104.7	-10,401.8	15,159.1	4,757.3
11	400	9,286.8	-9,628.9	-10,964.3	15,531.1	4,566.8
12	400	3,560.6	-4,551.9	-4,835.5	5,059.5	224.0
13	490	12,839.8	301.1	-12,208.3	18,122.1	5,913.8
14	500	-6,179.3	-6,894.3	-4,968.8	8,685.0	3,716.1
15	550	-17,409.6	-16,756.2	-5,057.2	8,198.5	3,141.3
16	550	5,127.0	7,427.7	-5,708.3	5,507.7	-200.6
17	570	4,446	-1,254.0	-7,998.0	13,483.7	5,485.7
18	620	-5,905.3	-4,635.1	-5,319.6	11,492.7	6,173.2
19	660	12,243.2	-3,173.0	-10,846.1	13,122.5	2,276.4
20	740	23,729.2	1,796.5	-23,251.1	18,420.8	-4,830.3
21	780	-17,024.2	-12,387.1	-5,940.5	10,722.3	4,781.8
22	800	10,409.8	-4,512.9	-17,129.7	13,286.3	-3,843.3
23	860	27,688.6	-4,005.2	-30,814.8	29,375.9	-1,438.9
24	980	10,871.2	105.6	-10,984.7	17,943.2	6,958.5
25	1030	11,802.8	-3,434.7	-9,568.3	11,986.3	2,418.0
26	1040	12,624.9	-12,279.1	-20,482.4	23,032.5	2,550.1
27	1040	4,415.8	-8,060.3	-12,743.3	11,652.0	-1,091.3
28	1050	-1,190.4	-6,126.6	-6,209.7	10,233.0	4,023.3

29	1270	-8,168.4	-15,097.3	-8,140.3	12,052.5	3,912.2
30	1290	12,437.1	7,516.3	-7,913.5	8,861.6	948.0
31	1350	18,858.4	6,313.5	-17,242.4	18,770.5	1,528.1
32	1650	7,151.0	3,444.0	-9,311.1	12,916.8	3,605.7
33	1670	9,454.0	-570.6	-5,987.9	6,846.5	858.6
34	1770	4,483.3	-20,458.7	-22,756.8	26,675.3	3,918.5
35	1950	6,704.6	-5,819.2	-6,940.0	8,695.3	1,755.3
36	1980	-5,807.0	-3,479.9	-3,064.73	3,581.1	516.4
37	2100	11,422.3	-15,581.1	-18,506.0	23,047.2	4,541.2
38	2230	10,702.0	-1,502.6	-17,734.9	14,752.2	-2,982.8
39	2340	3,829.3	-6,813.0	-5,959.2	5,942.1	-17.1
40	2430	8,541.2	-2,205.4	-7,992.1	8,791.6	799.6
41	2600	11,792.8	-11,707.1	-20,699.4	31,059.7	10,360.3
42	2650	8,941.7	15.7	-14,895.5	16,821.6	1,926.1
43	2770	-736.6	-7,571.2	-8,766.5	8,210.8	-555.7
44	2790	-394.8	-579.05	-9,201.2	9,775.3	574.0
45	2840	-1,281.4	-7,641.1	-13,652.0	21,190.0	7,538.0
46	2900	28,082.8	-4,713.2	-28,981.9	29,431.4	449.5
47	3150	10,229.9	-5,140.8	-13,053.2	15,517.9	2,464.8
48	3400	19,803.5	691.1	-16,147.9	16,011.1	-136.8
49	3940	30,702.5	-4,320.4	-31,094.4	25,673.8	-5,420.6
50	5050	24,382.8	2,104.3	-17,554.3	26,542.5	8,988.3
51	5810	8,442.9	-3,402.7	-7,360.6	7,717.3	356.7
52	7660	-31,952.9	-21,169.028	-725.1	1,262.0	536.9

Table A.4. Differences in individual hydrologic features as estimated by the MODFLOW-UZF model for each scenario of water extraction from the saturated zone.

Scenarios of Water Addition to the Saturated Zone						
Individual MODFLOW-UZF Components						
All Values Expressed as (Baseline Scenario - Stress Scenario)						
Total Stress Volume = 30,861 m^3						
Scenario #	Canal Seepage (m^3)	MODFLOW Accretion (m^3)	MODFLOW/Glover ratio	Change in Groundwater Storage (% of stress volume)	Avg. T (m^2/wk)	Avg. S_y
1	198.0	29,062.0	0.95	-0.03	3078	0.269
2	607.0	26,168.0	0.87	-0.06	2957	0.158
3	2,845.0	28,577.0	0.93	0.00	2754	0.171
4	760.0	14,117.0	0.45	0.39	3316	0.209
5	-350.0	27,016.0	0.88	0.08	4632	0.245
6	655.0	29,914.0	0.96	-0.05	7100	0.243
7	1,140.0	13,081.0	0.42	0.37	3881	0.23
8	1,850.0	25,881.0	0.84	0.02	6322	0.141
9	760.0	26,219.0	0.85	-0.04	3316	0.209
10	18.0	22,929.0	0.75	0.11	6352	0.237
11	65.0	22,512.0	0.73	0.12	5980	0.234
12	142.0	29,863.0	0.97	0.02	4296	0.233
13	2,111.0	20,395.0	0.66	0.08	4379	0.138
14	-311.0	13,248.0	0.43	0.46	6086	0.228
15	-559.0	2,530.0	0.12	0.84	3440	0.215
16	5,205.0	25,883.0	0.84	0.01	2754	0.171
17	100.0	25,045.0	0.81	0.01	1601	0.142
18	1,831.0	11,610.0	0.38	0.36	7124	0.169
19	626.0	28,949.0	0.94	-0.03	6717	0.238
20	620.0	35,581.0	1.15	-0.01	2458	0.243
21	1,932.0	3,215.0	0.11	0.68	4110	0.219
22	-21.0	33,893.0	1.10	0.03	4150	0.23
23	7,660.0	20,932.0	0.68	0.12	3446	0.336
24	5,727.0	13,693.0	0.44	0.15	6711	0.137
25	2,478.0	22,801.0	0.91	-0.07	6086	0.228
26	970.0	21,389.0	0.69	0.20	8164	0.246
27	-83.0	31,210.0	1.05	0.03	3843	0.228
28	5,615.0	2,346.0	0.12	0.61	4612	0.226

29	12,280.0	2,107.0	0.06	0.41	4657	0.222
30	-875.0	28,307.0	1.08	0.08	3204	0.224
31	13,394.0	17,086.0	0.56	-0.03	3287	0.144
32	420.0	26,045.0	0.84	0.03	3795	0.222
33	189.0	27,513.0	0.89	0.08	4313	0.181
34	178.0	8,341.0	0.27	0.60	3524	0.208
35	569.0	27,022.0	0.88	0.04	4334	0.179
36	27,262.0	300.0	0.01	0.09	4127	0.198
37	6,269.0	12,307.0	0.40	0.25	2404	0.144
38	3,195.0	30,345.0	1.01	0.01	2964	0.214
39	27,212.0	575	0.01	0.10	3638	0.189
40	-186.0	26,084.0	0.85	0.13	4112	0.177
41	5,651.0	5,029.0	0.16	0.32	3267	0.147
42	736.0	22,948.0	0.74	0.17	2714	0.196
43	26,389.0	694.0	0.03	0.14	2708	0.174
44	1,568.0	21,519.0	0.05	0.88	8697	0.198
45	2,897.0	5,078.0	0.16	0.50	1600	0.148
46	2,478.0	22,801.0	0.73	0.17	2180	0.191
47	1,082.0	23,905.0	0.77	0.12	3674	0.176
48	1,290.0	22,020.0	0.71	0.25	2681	0.193
49	4,820.0	25,343.0	0.82	0.20	2357	0.19
50	5,211.0	0.0	0	0.53	1566	0.16
51	4,075.0	588.0	0	0.84	2638	0.196
52	-1,649.0	11.0	0	1.02	1554	0.18