EFFECTS OF GROUNDWATER PUMPING FOR WATER TRANSFERS ON GROUNDWATER ELEVATIONS IN THE SACRAMENTO VALLEY AND MODELING STREAM/AQUIFER INTERACTIONS COMPARED TO ANALYTICAL SOLUTIONS

A Thesis

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California State University, Chico

In Partial Fulfillment of the Requirements for the Degree Master of Science in Interdisciplinary Studies

by
Kyle Morgado

Spring 2013
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ON GROUNDWATER ELEVATIONS IN THE SACRAMENTO
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ABSTRACT

EFFECTS OF GROUNDWATER PUMPING FOR WATER TRANSFERS
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The procurement of water for the growing population in California has many consequences when water demands exceed what can be supported locally. Transferring water out of the Sacramento Valley has been done for approximately 80 years since the construction on the Central Valley Project, and additionally the State Water Project some 20 years later. The subsequent source of water that is being considered to supplement the out of region transfers is the groundwater supplies found in the Sacramento Valley. The Sacramento Valley is the main source of water for the Great or Central Valley of California. The focus of this work is on the impact of groundwater use in the
Sacramento Valley, to gain a better understanding of the groundwater resources and how to better manage them. This project employed a groundwater model to predict effects of pumping on groundwater supplies. This research effort is conjoined with a project investigating the validity of a new method for obtaining accurate streambed conductances for finite difference modeling using a specific grid size around streams. In large-grid models, the flow lines from the vertical leakage of a stream/river to the horizontal flow of the groundwater is difficult to model within a finite-difference cell due to the inability for the flow to “turn” from the vertical to horizontal as it would naturally. To model stream/aquifer interactions, a properly refined three-dimensional grid is needed. A promising solution proposed by Dr. Morel-Seytoux uses an analytical solution that can be used in two-dimensional finite-difference models to calculate the conductance as a function of grid size. This thesis investigates the efficacy of this approach for various stream geometries and flow configurations.

Ultimately, this thesis demonstrates the use of regional scale models to predict the temporal and spatial change in water table elevation and aquifer storage along with new methods to further improve the accuracy of regional scale models for local use through better representation of stream aquifer interactions. The results are important for using regional models for investigations of aquifer health, storage depletion, and water table elevations.
CHAPTER I

INTRODUCTION

Motivation

The procurement of water for the growing population in California has many consequences when water demands exceed what can be supported locally. Many high population centers are located near the ocean far from large fresh-water supplies. Population is directly proportional to water demand and if the regional population grows it may exceed local sustainable sources of water, both surface and groundwater, and lead to the need for procuring water from outside of the region. Procuring water from sources outside of a population’s local area can be challenging due to conveyance limitations. Conveyance can be difficult due to topography, distance, water rights, and cost. Water is a highly contentious topic in California and the need to better understand California’s groundwater movement increases as water tables decline. The focus of this work is on the impact of groundwater use in the Sacramento Valley and to gain a better understanding of the groundwater resources and how to better manage them. The focus of this thesis is to apply groundwater models to predict effects of pumping on groundwater supplies.

The project uses groundwater modeling, specifically the United States Geological Survey’s (USGS) Central Valley Hydrologic Model (CVHM) (Faunt, 2009) which is a model built with MODFLOW (Harbaugh, 2005), a finite difference groundwater modeling program.
The dynamics of using regional scale models, like the CVHM, for smaller scales can be problematic because in the process of refining a large grid the recalibration of parameters can be difficult, especially the conductance of the streambed. Dr. Hubert Morel-Seytoux has been developing a method for a “turning factor” (Morel-Seytoux, 2009) that may be adapted to a Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW) model to improve simulated accuracy of stream/aquifer interactions. The testing and analysis of this new method will further the knowledge of both stream/aquifer interactions and application of regional scale models to local scale flow processes.

Purpose

The purpose of this investigation is to better understand the impact of pumping groundwater on large scales for conjunctive use and water transfers and to improve simulations of stream/aquifer interactions by combining analytic solutions with a finite difference grid. The larger project that this modeling effort is a part of studies the economic impact of declining water tables. The impact of larger lift costs and the need to extend wells that may be too shallow if the water table decline is greater than the well depth could lead to economic and social issues. This thesis will focus on modeling the Sacramento Valley groundwater system to make estimates of possible water table trends, water table drawdown, and changes in groundwater storage. The need to interpret stream aquifer interactions more effectively while going from regional scale models to local scale models is addressed by investigating how analytical solutions can help describe
stream/aquifer interactions within a finite difference model and create a flexible and scalable method that can be used with varying discretization.

The purpose of modeling the Sacramento Valley and the effects of increased pumping on the water table elevation is to simulate the spatial and temporal effects of pumping. Pumping groundwater changes the amount of water in storage, the amount derived from a source, and/or the amount of water that is no longer discharged from the system (Theis, 1940). Temporal effects of pumping are compounded by repeated pumping before a cone of depression can fully recover. The superposition of pumping can lead to compounded drawdown if pumping occurs before the time to rebound is obtained. There are eight different pumping scenarios that will be focused on in this thesis. The pumping scenarios focus on drawdown due to pumping and the time required to recover the lost storage.

Pumping affects storage and can also affect stream flow. When simulating stream/aquifer interactions with a finite-difference model, it can be problematic to get vertically flowing water from stream leakage into a mostly horizontally flowing groundwater aquifer system. This can be dealt with by calibration factors or by having a refined grid that accounts for proper vertical and horizontal components of stream leakage. An analytical solution for stream leakage that can be adapted to a finite-difference grid could help with model calibration and accuracy. The accuracy of such an analytical solution as proposed by Dr. Hubert Morel-Seytoux (Morel-Seytoux, 2009), can improve the ability of large grid, regional models to simulate local-scale stream/aquifer interactions. These proposed methods are investigated under changing discretizations and pumping scenarios to test the ease of use and accuracy of the proposed coupling of
analytic and finite-difference solutions. These results have implications for using regional scale models, like the CVHM, for simulating phenomena at more localized scales.

Scope

An Agriculture Research Institute (ARI) grant to investigate water table decline due to large scale pumping for water transfers is the impetus for the modeling scenarios in this investigation. The scope of the (ARI) project is the Sacramento Valley focused mainly in the Butte and Colusa basins. The Central Valley Hydrologic Model (CVHM) represents the entire Central Valley. The ARI project examines the effect of groundwater pumping for water transfer out of the region. The pump is located east of Willows, CA, west of the Sacramento River and is a single pump as shown in Figure 1. The pumping occurs from the third layer in the model.

Figure 1. Well Location in model, east of Willows, CA, west of the Sacramento River, extraction from third layer of the model.
Due to the one mile by one mile grid discretization, it can be treated as a single pump or many pumps in a square mile that are effectively pumping from the center node of the cell. The area was selected because of the large amount of agriculture and similarity in pumping location examined in the Sacramento Valley Groundwater Model (SACFEM) discussed later. The ARI project focuses on the Northern Sacramento Valley, however the entire Central Valley is simulated; therefore the effects of pumping will not be affected by artifacts from artificial boundary conditions in the study area. The scope of the project is to study the effects of differing pumping rates on the annual average water table elevation compared to a non-pumping base set of years. The only difference between the base model and the model with the pumping for water transfers is the pumping rate itself. This ensures that any changes in water table elevation are caused only by pumping. Other factors that may affect the simulated response to pumping, such as changes in precipitation, were not considered.

The scope of the mode used to studying the “turning factor” (Morel-Seytoux, 2009) are hypothetical and investigate the relationship between model discretization and an analytical solution for stream/aquifer interactions in steady-state situations. Changes in stream geometry including rectangular and trapezoidal cross-sections, and various degrees of penetration are investigated. Furthermore, the addition of pumping and its effect on simulated stream/aquifer interactions is also investigated.

MODFLOW is used for all simulations. The ARI project utilizes the USGS’s CVHM (Faunt, 2009). The CVHM was designed to calculate change in storage, groundwater flow, and subsidence in the Central Valley. Model Muse (Winston, 2009) is used to construct models that test the analytic solution of stream/aquifer interaction.
Model Muse is a graphical user interface (GUI) that enables building a MODFLOW model in a GUI format.
LITERATURE REVIEW

Groundwater Fundamentals

Groundwater movement can be mathematically described using Darcy’s Law, as shown in Figure 2, where $k$ is hydraulic conductivity and $\frac{dh}{dx}$ is the head gradient. In addition, other fundamentals like Theis’ “The Source of Water Derived from Wells” (1940) explains that pumped water has to come from some combination of three sources and that the hydrologic cycle is a closed loop.

![Figure 2. Darcy’s Law.](image)
Groundwater systems have longer memories than surface water bodies because of the slow movement of groundwater compared with the movement of surface waters. Groundwater is stored in pore space and moves due to a hydraulic head gradient. Surface water flows through channels, is mainly slowed by elevation changes, and can move rapidly from one place to another. In contrast, groundwater must flow through a myriad of materials which can have very heterogeneous transmissive properties. The complexity and heterogeneity of aquifer systems and the inability to view the system, while surface water can be interacted with and seen through its entire flow, adds a different intricacy to groundwater than surface water.

Central Valley Hydrologic Model

The Central Valley Hydrologic Model (CVHM) (Faunt, 2009) is a MODFLOW model that was constructed by the United States Geological Survey (USGS). The CVHM uses a discretization of 10 layers, 440 rows, and 98 columns, and couples surface flows and deliveries as well as land use information with groundwater flow and elevations. The CVHM uses a module called the Farm Process (FMP) (Schmid, Hanson, Maddock, & Leake, 2006) to incorporate land use and associated evapotranspiration (ET), and surface water and groundwater deliveries, to calculate groundwater extraction and deep percolation. The different packages used in the CVHM (Faunt, 2009) along with the added package for the pumping for water transfers are shown in Figure 3.
### Input Modules for CVHM

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<td>DIS</td>
<td>Discretization</td>
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<td>GHB</td>
<td>General Head Boundary</td>
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<tr>
<td>FMP</td>
<td>Farm Process</td>
</tr>
<tr>
<td>HFB6</td>
<td>Horizontal Flow Barrier-for fault lines</td>
</tr>
<tr>
<td>LPF</td>
<td>Layer Property Flow</td>
</tr>
<tr>
<td>PCG</td>
<td>Preconditioned Conjugate Gradient</td>
</tr>
<tr>
<td>SFR</td>
<td>Stream Flow Routing</td>
</tr>
<tr>
<td>SUB</td>
<td>Subsidence</td>
</tr>
<tr>
<td>MNW1</td>
<td>Multi-node Well</td>
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<tr>
<td>Wel</td>
<td>Well (added for project simulation)</td>
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*Figure 3.* Input packages for Central Valley Hydrologic Model simulations of additional groundwater pumping for water transfers.

**Agricultural Economy**

The agricultural economy in the Central Valley of California is a multi-billion dollar industry that depends on water availability (Faunt, 2009). California is a multifaceted ecological environment with watersheds that are impacted by desertification, snowpack, and reservoir operations. California’s water issues are controversial because the abundance of available water is not always where the crops, urban demands, or industrial uses need the water. The spatial separation of water users and water supplies has led to many water projects, mainly the Central Valley Project (CVP), built by the
United States Bureau of Reclamation (USBR), the State Water Project (SWP), constructed by the state of California, and the Colorado River pipeline that delivers water to southern California water users. Water transfers are largely driven by agricultural needs of the southern central valley and metropolitan use in the Los Angeles Basin.

Sources of Water to Wells

There are three fundamental sources of water to a pumping well, (1) induced recharge, (2) reduced discharge, and (3) mining of groundwater from storage, shown in Figure 4. Pumping groundwater is not offset by virgin recharge; the water must come from some combination of these three. Reduced discharge can be the reduced evapotranspiration (ET) of local flora or of limiting virgin discharge to streams, springs,

*Figure 4. Three sources of water to a well: Reducing storage, reducing discharge, inducing recharge.*
etc. Induced recharge can be inflows from a lake, stream or some other source of water. Mining of water is pumping from an aquifer and a corresponding drop in hydraulic head and water table level from extraction of groundwater from the pore space in the aquifer material (Theis, 1940).

Groundwater Model Scales, Types and Uses

Modeling can be used to better understand the spatial changes within an aquifer system by varying the stresses on the modeled system and analyzing the effects. Groundwater modeling can be performed at small or large spatial scales. Matching the correct model for the study area is the first step in effectively using models to make predictions of future groundwater characteristics or possible effects on the hydrologic cycle. Looking at the hydrologic cycle as a whole is very important for modeling groundwater systems. There are many different methods that can be used to model groundwater but the models that are used most frequently are either based on the finite difference or finite element method. One model that is widely used in California is the Department of Water Resources Integrated Water Flow Model (IWFM). This model uses the finite element method and couples surface and groundwater flows (California Department of Water Resources, 2012). It is a modeling program much like MODFLOW that can be used to build a model of a groundwater system. DWR’s California Central Valley Groundwater-Surface Water Simulation Model (C2VSim) (Brush & Dogru, 2012) is built using IWFM as well as the Butte County Department of Water and Resource Conservation’s (BCDWRC) Butte Basin Groundwater Model (CDM, 2008). The finite
element grid used in both models varies from 8000ft to 500ft discretization depending on the location in either model (Brush & Dogru, 2012).

Butte Basin Groundwater Model

The model boundaries are roughly the Sutter Buttes in the south, Deer Creek in the north, the Sacramento River in the West and the foothills to the East. The model is broken into 35 sub-regions with 3770 nodes with higher resolutions around the Chico area and Princeton area. For land use, four land use varieties were used; agricultural, urban, native and riparian. The period simulated in the Butte Basin model is from 1970-1999 using data from this period for precipitation, stream flow, land use, and agricultural diversions. The model was developed to study the effects of possible cutbacks in water delivery from the State Water Project (SWP) and the effects on the groundwater elevations. The simulations compared results without cutbacks and the Water Management Scenario with the cutbacks. Water Management Scenarios are the base scenario with the new water management changes (i.e., surface water cutback and added pumping that were used to investigate changes due to the new water management policy). The cutbacks were made up by land fallowing and additional groundwater pumping in the basin. All other characteristics of the model were held the same. The model concluded that drawdown was limited due to the cutbacks and drawdowns of more than two feet were localized around the additional pumping sites (CDM, 2008).

C2VSIM

the C2VSIM, land use practices are broken into four categories; agricultural, urban, native, and riparian with infiltration and runoff being calculated by NRCS curve number method. The groundwater system is a three-layer system of confined and unconfined aquifers with horizontal and vertical flow, with the top-most layer representing the unconfined, unsaturated layer. Pumping is input either as a regional amount or individual wells. The C2VSIM model is composed of 1393 nodes and covers the entire Central Valley, with 449 river nodes. The C2VSIM regional model is much like CVHM model in the objective of simulating surface water and groundwater including change in storage, groundwater flow, stream depletion and subsidence (Brush & Dogru, 2012).

SACFEM

A recently implemented model for Glenn Colusa Irrigation District and the Natural Heritage Institute is the Sacramento Valley Groundwater Model (SACFEM) by CH2MHiIl and MBK Engineers. The base modeling program used to construct SACFEM was MicroFEM, a groundwater modeling system developed in the Netherlands for modeling saturated single-density groundwater flow (Lawson, Bourez, & Bergfeld, 2010). The SACFEM model simulated the years from 1922-2003. SACFEM can include no flow, specified flux and head dependent boundary conditions. The local model included no flow boundaries at the model borders, head dependent boundaries for rivers and streams, specified flux for precipitation and agricultural deep percolation, mountain front recharge and urban pumping. The pumping varied between 100,000 acre-feet/year to 300,000 acre-feet/year spread between Glenn County and the Butte Basin. The model also included reservoir operation changes to simulate conjunctively using storage in reservoirs more aggressively with groundwater substitution. The CVP-SWP System
Simulation Model (CALSIM II) which was developed and is used by California DWR outputs were used to drive the surface water components of the model (Lawson et al., 2010). The model is being continually refined by Glenn-Colusa Irrigation District (GCID) but focused on what could have happened with water table elevations and storage in the past. The SACFEM model did indicate some stream impacts to Butte Creek at the high end of pumping rates.

The models described above were constructed to investigate different parts of the Central Valley. SACFEM focuses on the Sacramento Valley north of Sacramento, the Butte Basin Groundwater Model focuses only on the Butte Basin, and DWR’s model simulates the entire Central Valley. The Butte Basin Groundwater Model, SACFEM and C2VSIM simulate past conditions but have not been used to apply the most recent land use with projected pumping to investigate future impacts on water table decline. The Butte Basin Model looks into pumping for substitution but during the period of time from 1970-1999 and only for irrigation use when surface water allotments are reduced.

**Boundary Conditions**

In a groundwater flow model, boundary conditions are the sources and sinks of water. Without boundary conditions the model would not be able to start or have a constraint that must be met, therefore be unsolveable. The boundary conditions that are typically used, for example, in the CVHM, are no flow boundaries, general head boundaries, stream/river heads, and precipitation. Many of these boundaries represent surface water flows and the need in a groundwater model to have surface water boundary conditions demonstrates the interconnectivity of the hydrologic cycle. Surface water and
groundwater should be treated as a single source because of their interconnectivity. The interconnectivity of surface water and groundwater illustrates the need to better understand the interaction between the two and the importance of properly modeling stream/aquifer interactions (Franke, Alley, Harvey, & Winter, 1998).

Understanding the interconnectivity of surface and groundwater systems while building groundwater models is important. Building a groundwater model must take into account all boundary conditions that are relevant and work within a concept of how the system should react to what one is modeling before the model is built (Franke & Reilly, 1987).

Stream/Aquifer Interactions

A river is deemed “connected” if the stream/river gains or loses water in accordance with water table changes, as shown in Figure 5. A disconnected system is one

![Figure 5. Cross sectional view of connected stream.](image)
where local water table changes do not affect the stream flow, Figure 6. The term disconnected stream/aquifer system is a misunderstood relationship. To say

"disconnected" and meaning that one cannot affect the other is a misnomer. A stream/river will still lose water to the aquifer through gravity seepage, and most streams/rivers are not disconnected for their entire length as shown in Figure 7. Therefore, disconnected does not mean that the two reside totally separately but that in a short length of stream local water table depletions might not effect a stream locally but may lead to further river disconnection and additional decline of the water table due to less water being available through leakage to recharge the aquifer. The best description of

Figure 6. Cross sectional view of disconnected stream.

Figure 7. Profile view of stream and how a stream can alternate from connected to disconnected.
a disconnected system is a system in which the zone between the aquifer and the stream is unsaturated. As described in by Franke et al. (1998) streams/aquifers interact in these three ways; connected, disconnected and sometimes both along the stream length. Stream/aquifer interactions involve not only water transport but also solute transport. The flow of contaminants between surface water and groundwater illustrates the need to better understand the connection of surface and groundwater for more than depletion and recharge but for the transport of hazardous materials. Figure 8 illustrates the interconnectivity of not only streams with aquifer systems but also recharge from precipitation and deep percolation from agricultural irrigation.

Figure 8. Hydrologic cycle interaction between surface water and groundwater.
These are additional flows between surface water and groundwater that can lead to depletion, recharge and transport of surface contaminants to the groundwater, and the pumping shown illustrates the potential to bring contaminated groundwater to the surface (Franke et al., 1998).

Modeling stream interaction with an aquifer in MODFLOW is done in a variety of ways. Some of the different methods used to effectively simulate the dynamics of the interaction are to calibrate the stream bed conductance or discretize the grid small enough in comparison with the stream feature. The relationship between stream/aquifer interaction and grid size and the size of a stream feature was investigated by Haitjema, Kelson, and Lange, 2001. They identified a characteristic leakage length, Figure 9, lambda that is a function of transmissivity of the aquifer and the vertical resistance of the streambed.

\[ \lambda = \sqrt{kHc} \]

- \( k \) = hydraulic conductivity
- \( H \) = aquifer thickness
- \( c = \) resistance, \( d/k_v \) where,
- \( d \) is the thickness of the aquitard (streambed or clogging layer) and \( k_v \) is the vertical hydraulic conductivity.

Figure 9. Characteristic leakage length for streambed layer identified by Haitjema, Kelson, and Lange (2001).

This work helped identify the grid size needed to properly model stream/aquifer interactions, but they only investigated 2-D models of horizontal flow for the characteristic leakage length and not fully 3-D models including the horizontal and
vertical components. The need to either correct for the grid size error or to refine the grid, which means more computation time, is a limitation of a finite difference model (Haitjema et al., 2001).

Stream Depletion

Stream depletion is the extraction of stream flow due to pumping. Stream depletion modeling can help local, state and federal governments, and interest groups to better understand how to control the use of groundwater to lessen the effect of human water usage on the environment. Stream depletion has effects on surface water rights holders, and in extreme cases, can change water rights completely as occurred in Colorado where water rights laws were changed to include ground water (Bredehoft, 2010). In Colorado, it was found that groundwater pumpers who installed wells because of their lack of surface water rights directly affected the flow of the surface water, effectively taking water that was already adjudicated to other water rights holders. This led to a change in water rights laws to include ground water users as junior water rights holders and that pumping could not negatively affect the water rights of the more senior surface water rights in an area. This contributed to the fallowing of thousands of acres of land in order to return the system to a sustainable state that produced enough flow for environmental requirements and the senior water rights holders (Bredehoft & Young, 1983). This is a case where the system could have been modeled before the wells were installed, and the issue of groundwater pumping depleting the nearby streams could have been potentially recognized and mitigated before it occurred.
Stream Depletion Factor

Stream depletion due to pumping can vary because the amount of time it takes for a cone of depression to reverse groundwater gradients from the stream. These concepts were first investigated by Theis (1941) and then refined by Glover (1958, as cited by Jenkins, 1968) (see Figure 10). The impact of pumping will first reduce discharge if the stream is a gaining stream and eventually can lead to inducing recharge (taking) from the stream.

Glover’s Solution:

\[ q = Q \text{ erfc}(a^2S/aTt)^{1/2} \]

where:

- \( q \) = amount of water taken from stream
- \( Q \) = amount pumped by well
- \( t \) = time since pumping was started
- \( a \) = distance of well from stream
- \( S \) = Storativity of the Aquifer
- \( T \) = transmissivity of the aquifer

Figure 10. Glover’s solution to alternative solution to the analysis of Theis on the effect of pumping on streams as derived in Theis’ 1941.

Reducing surface water diversions to account for stream depletion due to groundwater pumping can only be effective if the groundwater pumping affects the stream directly. A pumping site that has the potential to deplete a stream during the growing season due to its distance from the stream and the aquifer diffusivity (T/S) will take from the mitigated diversions (Jenkins, 1968). A groundwater pump that is not located in a way to take advantage of this mitigation will either take from storage or take from the stream after the water has already “gone by.” In the latter case, the diversion
simply leaves the system and the pumping will lead to stream depletion during the non-agricultural season. Thus, the reduced diversion simply puts more water in the channel during the summer months to the detriment of winter flows.

Groundwater pumping effects on stream depletion should be examined beyond the pumping season because in many instances the residual effects of pumping are greater than the effects while pumping (Kendy & Bredehoft, 2006; Jenkins, 1968). Water has to come from somewhere; therefore to achieve a steady-state system, the depletion due to pumping has to eventually equilibrate with inflow (Theis, 1940). The residual effects of pumping on stream depletion must be looked at temporally until the pumping matches the depletion. If a stream is modeled as a constant head boundary and the aquifer is homogeneous and extends infinitely, a stream depletion factor can be used to calculate the effect pumping has on a stream. Jenkins (1968) created a stream depletion factor (SDF) (Equation 1: \( SDF = \frac{a^2 S}{T} \)) to help understand the impacts that wells pumping in aquifers of the similar characteristics would have on nearby streams. His work is based on earlier work by Theis (Theis, 1941) and the Glover solution, Figure 11 (Jenkins, 1968). By rearranging Glover’s solution, Jenkins came up with the stream depletion factor (SDF) (Equation 1: \( SDF = \frac{a^2 S}{T} \)). Stream depletion factors as shown in the

\[
\frac{q}{Q} = \text{erfc} \left( \frac{SDF}{4t} \right)^{1/2}
\]

*Figure 11. Glover Solution Rearranged by Jenkins.*
equation help to solve analytically for the amount of water taken from a stream by a nearby well.

The stream depletion factor can be viewed a characteristic time constant and used in dimensionless plots. This allowed for quicker comparison of alternatives without having to evaluate the complementary error function (erfc) which was difficult in 1968 because of the lack of computing power available.

Surface water diversions or exercising of surface water rights immediately affects surface flows by diverting flow away from the stream onto farms. In contrast, pumping takes more time to affect the stream because of the time it takes for a cone of depression and groundwater gradients to reverse at the stream/aquifer interface. Pumping groundwater instead of taking directly from a stream may lessen the immediate effect of stream depletion at that point in time due to the time it may take for pumping to affect a stream. However, the total volume extracted must be balanced in the system. This volume comes from a longer period of stream depletion at a lower rate of withdrawal (Bredehoft & Young, 1972). Residual effects cannot be ignored because they vary by the well’s distance from the source of water, the aquifer’s diffusivity, and the residual effects can be greater than the immediately seen effects (Jenkins, 1968).

Turning Factor

The “turning” factor proposed by Morel-Seytoux, could be of great use once it can be integrated effectively with a finite-difference grid. To be effective, it must work efficiently and be an easier and more accurate than the presently used clogging layer (Morel-Seytoux, 2009).
The interconnection of surface and groundwater illustrates the need to properly model the physical connection of groundwater and surface water and how water moves from one part of a system to another part of the system (Bredehoft, 2010). The modeling of stream/aquifer interactions is difficult because modeling streambed conductance and the change of flow direction from mostly vertical to horizontal. There are ways to alleviate this by using a streambed conductance coefficient that has to be changed with grid size and stream size. The streambed conductance coefficient also accounts for other errors that might not have anything to do with the streambed, like the loss in flow through the water changing direction, and therefore cannot be used in predictive models as these conditions are likely to change over time. The development of a “turning” factor to get the vertical seepage from a stream to horizontal flow in an aquifer in a larger grid system is a proposed approach for modeling this three-dimensional, small-scale flow while using a large-scale finite-difference model. The advantage of this approach is it is a known function of grid size and accounts for streambed conductance with the “turning” factor.

Pumping and Consumptive Use

Pumping groundwater has many effects on aquifers and streams. However, it is not the act of pumping that is detrimental to aquifers and streams; it is the consumptive use part of applied water that does not go to deep percolation and is lost from the local system (Kendy, 2003).

The view that less pumping is what is needed to reduce impacts of groundwater use does not take into account the hydrologic cycle as a whole. It is not only
the amount of water that is pumped from the system that causes groundwater tables to decline but also the amount that is consumptively used through evapotranspiration, Figure 12. A way to stabilize groundwater levels is to decrease ET (Kendy, 2003). This is water that is taken from the aquifer that cannot return to the aquifer through deep percolation, Figure 13. If x amount of water is pumped and used to irrigate but only 0.5x is transpired, the rest can potentially return to the aquifer through deep percolation.

Figure 12. Applied water to a crop either goes to consumptive use ET or deep percolation. In some instances over irrigation or flood irrigation can lead to runoff.

\[ \text{Applied Water} = \text{Consumptive Use} + \text{Deep Percolation} + \text{Surface Runoff} \]

Figure 13. Applied water breakdown.
But if more crops are irrigated with this water by fully utilizing 0.75x of the pumped water then there is a 50% increase in water lost from the aquifer system. Therefore, it is “the above ground consumption rates that are key to sustainable pumping” (Kendy, 2003). A break down of efficiency and how it is calculated is shown in Figure 14. In this example, it is assumed that there no surface runoff.

<table>
<thead>
<tr>
<th>10 acre-ft Applied at 70% efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 acre-ft= 7 acre-ft Consumptive use + 3 acre-ft Deep Percolation</td>
</tr>
<tr>
<td>10 acre-ft Applied at 95% efficiency</td>
</tr>
<tr>
<td>10 acre-ft= 9.5 acre-ft Consumptive use + .5 acre-ft Deep Percolation</td>
</tr>
</tbody>
</table>

*Figure 14. Breakdown of how efficiency works, more efficient means higher percentage of water that goes to consumptive use.*

**Conjunctive Use**

Conjunctive use is the process of using surface water and groundwater together to irrigate and provide water. Effective conjunctive use practices can lead to a more stable system, (Bredehoft, 2010). Pumping groundwater can dampen surface allocation effects. Using groundwater during dry years and using less surface water for irrigation can help surface water quantities stabilize and spread recovery of the system year around. This is in contrast to relying solely on surface water reservoirs, which only recover during high flows or by reducing outflows to further limit depletion. Conjunctive use practices, while more difficult to understand, allow for the whole water cycle to be better understood and managed (Bredehoft, 2010).
Timing is important when using groundwater conjunctively with surface water. If the needed water is not delivered at the right time at the right place, the efficiency of the process could be hindered. Transmissivity is a measure of an aquifer’s ability to transmit flow through the aquifer. It is the hydraulic conductivity (k) of the aquifer multiplied by the aquifer thickness (b), Figure 15. If an aquifer is very diffusive the effects of pumping can transmit quickly away from the pumping site. This can occur in aquifers with high transmissivity or low storage coefficient. Storage and transmissivity together control the speed of the signal propagation from the pumping site.

Figure 15. Homogenous flow through a control volume, and representation of transmissivity.

Highly transmissive material with low storage will produce rapid growing cones of depression because the aquifer can easily move water but there is low storage of water therefore the storage is depleted quickly.
Applied water for agricultural irrigation is either consumptively used, lost to deep percolation or to surface runoff. Runoff is due to high water application for specific crops in specific areas. For example, rice, where water is used for weed control. Another example is wild flooding of non-improved hillside pastures by releasing water from surface ditches without leveling or channels to direct flow. For the purpose of investigating the impacts of more efficient irrigation methods, flood irrigation that cannot be changed due to crop needs will be excluded. One of the impacts of more efficient irrigation methods is the loss of water to deep percolation. Deep percolation is one of the vehicles by which groundwater is recharged, Figure 16. High winter stream flows have

*Figure 16. Applied water that returns to an aquifer via deep percolation is what is not used by the phreatophytes through consumptive use.*

been attributed to deep percolation from agricultural irrigation maintaining groundwater levels through the dry summer months and the slow discharge via the stream/aquifer interaction (Bredehoft, 2010).
High winter stream flow is seen to be the normal flow because it has been the norm for so long, but using more efficient irrigation can lead to lower winter flows. This actually mimics the “natural” setting much more closely. Historically, aquifers were only recharged during the wet months with high water and flood events and slowly discharged this water to streams during the dry months. This would lead to low stream flows in the winter months leading up to the first rains. Irrigation of agriculture has led to the recharging of aquifers during the summer which allows streams to maintain higher flows until the rainy season. Therefore, when more of the applied water is used consumptively there is less water that escapes to deep percolation which can reduce winter stream flow in nearby streams. More efficient methods of irrigation can lead to more water going to the vegetation and less excess to deep percolation. (Kendy & Bredehoft, 2006)
CHAPTER III

METHODS

MODFLOW

MODFLOW was produced by the United States Geological Survey (Harbaugh, 2005) to model groundwater flow. MODFLOW was constructed in a modular fashion. Different modules were written to be read by the base MODFLOW program and turned on/off by the user. The modules used in this work are listed in Figure 3. MODFLOW is based on the finite-difference method, which is useful for representing spatially varying systems by discretizing them into a grid in which quantities can be assumed uniform. Spatial inputs that are commonly used are agricultural acreages, groundwater basin extents, geological extents as well as surface water bodies.

The groundwater modeling program, MODFLOW, as well Central Valley Hydrologic Model (CVHM) constructed with MODFLOW, are both tools that are used throughout the investigations that form this thesis. MODFLOW is a powerful tool for examining groundwater issues, but can be limited if applied using incorrect discretization or if the data is too limited to simulate the desired output. MODFLOW is applied in two areas of this thesis. The first was using the CVHM to examine the effects of using groundwater to supplement water transfer from Northern California to the rest of the state and the effects of the increased pumping on the valley’s groundwater elevations. The second application is to verify the validity of an analytical solution of stream aquifer
interactions and the discretization needed in a finite-difference model to obtain the same solutions. This also included testing the effects of different cell sizes and varying parameterization of the analytical solution inputs. The details of both these investigations are described in Chapters IV and V.

The effects of large scale pumping on water table elevations did not include analysis of the effects on streams. The whole Central Valley was modeled but only the outputs from the Sacramento Valley were investigated, Figure 17. The changes due to

*Figure 17. Well placement in Sacramento Valley for all scenarios and extent of area investigated.*
pumping for water transfers were localized in the Sacramento Valley showing very minimal to no change anywhere else in the Central Valley. The scenarios investigated focused on the effects of changes in pumping for water transfers and did not consider changes to crop patterns or crop type, precipitation, diversions or farm pumping to. Impacts of water table decline on crops were not investigated.

GIS

The use of a finite difference (FD) grid and its relative ease of inputting spatial data allows for coupling with Geographical Information Systems (GIS). These inputs can be land use data compiled by local, regional and state government as well as private companies. The spatially referenced data that is incorporated from GIS also includes geomorphology, well placement, stream reaches, locations of lakes, reservoirs, and land surface and water table elevation data. The ability to use GIS for inputs allows for pre–and-post processing to be done using more visual methods and makes the information more consumable for larger audiences. GIS is a tool that can be used to build input files for a FD model by applying changes to the FD grid in GIS and exporting the information into a format that MODFLOW can use. These processes can be facilitated with preprocessors to take GIS information and format them for MODFLOW.

Python

Python is an open source scripting language that can easily work with text (.txt), comma separated values (.csv), GIS files and many more file types, allowing for cross program pre and-post processing. Python is the coding language used to post process the information gathered from simulations to examine the effects of groundwater
pumping on water table elevations in the Sacramento Valley. A post processor was
developed, Appendix A, to either select single months or an average of a set of months
from every year of the model and output them as a yearly snapshot for every cell in the
model. This tool allows for the outputs from the model run, which are millions of lines
long, to be formatted into an array that can be then uploaded as a GIS table. The GIS
table can then be joined to an existing grid shape file in GIS. The grid can then be colored
by year and water table elevation to create colored maps of the model output. The
conversion from a text file array to GIS database file (.dbf) is done by copying the text
file output from the python post processor into Excel for every model run. This allows for
all eight scenarios to be graphed in Excel and to also build an Excel sheet that can be
exported to GIS to color the outputs that are needed to show a visual output of the
affected water table elevations.

Central Valley Hydrologic Model

The United States Geological Survey (USGS) developed a model of
California’s Central Valley called the Central Valley Hydrologic Model (CVHM). The
CVHM is a regional model that uses data obtained from state, federal and local sources
for the period of 1961-2003 with more updates scheduled. The CVHM can be used to
model changes in storage, groundwater drawdown, and stream depletion. The CVHM
takes into account land use processes, ground water extractions, streams/rivers, the delta
(as a general head boundary), precipitation and subsidence, to name a few. The
motivation to use the CVHM for this project was the vast amount of information that had
already been accumulated and the power of a tool like the CVHM from which to work.
The methods that were used in this modeling effort involved using the CVHM inputs as a starting point for a model and as a library of information from which to build the models that were needed to test the scenarios. The CVHM has a wealth of knowledge built into its database, including precipitation data for over forty years, land surface data, geomorphology of the central valley, and water table elevations. The data provided in the CVHM is a very strong base on which to build models going into the future. It is a source of information on what has happened in the past and allowing past scenarios to be used as future scenarios, much like testing the response of a building to an earthquake by using actual data obtained from an earthquake. The use of previous data allows for more natural modeling of future events by using events that have already happened and adding changes to these events that coincide with possible future deviations from past practices. The data from CVHM was used for base runs without pumping to produce the tables in Excel for graphing of water table drawdowns and to format the outputs with the correct headers for implementation into GIS for spatially referenced output, Figure 18.
Figure 18. Example and explanation of Excel input and output constructed to process data for graphs and GIS.
CHAPTER IV

GROUNDWATER PUMPING FOR WATER TRANSFERS AND THE EFFECTS ON GROUNDWATER ELEVATIONS IN THE SACRAMENTO VALLEY

Introduction

California’s history has been shaped by water. The Sacramento Valley, as shown in Figure 19, is the main source of water for California.

The Sacramento Valley has many creeks and rivers running through it, the largest of which are the Sacramento and Feather Rivers with annual flows on average of 24,000 cfs and 8,321 cfs, respectively (United States Geological Survey, 2013). The capture, channeling and piping of water to supply the state’s needs for urban and agricultural water has led to the construction of the Central Valley Project and the State Water Project. The Sacramento River is the beginning of the United States Bureau of Reclamation’s (USBR) Central Valley Project (CVP) (United States Bureau of Reclamation, 2013) and the Feather River is the start of California’s Department of Water Resources (DWR) State Water Project (SWP) (California Department of Water Resources, 2013). The two projects regulate the flows in the two natural waterways and convey water from the Sacramento Valley to the Southern Central Valley and beyond to the Los Angeles and San Diego Basins. The water that flows through the two projects
Figure 19. Model focus area-Sacramento Valley.

comes from surface water releases from several reservoirs, the main sites being Lakes Shasta and Oroville. The two reservoirs that control the flows are additionally used for flood control and to supply environmental flows. Due to the variety of water demands on these reservoirs, groundwater supplementation has been identified as a possible resource for water transfers and/or to increase environmental flows during years where the reservoirs may not meet the demands (Lawson et al., 2010).

The focus of this study is to investigate the impact of large-scale groundwater pumping, and the corresponding groundwater elevation declines in the Sacramento Valley. The impacts of pumping at a variety of rates and the possible effects on groundwater elevations both temporally and spatially are investigated using the Central Valley Hydrologic Model (CVHM) (Faunt, 2009).

Model Setup

The CVHM was setup for a ten year model run starting in 2003 and repeats the year 2003 for all ten years. The most recent land use, geology, well data, stream flow, and precipitation data are from the year 2003. Furthermore, this year was chosen because of the average (as opposed to wet or dry) type of precipitation that occurred in that year, as shown in Figure 20 (Faunt, 2009).

Using average conditions, rather than wet or dry, allows examination of pumping effects without the effects of extreme changes in weather patterns. The model simulated one year of pumping from layer 3, row 77, column 60, at a constant rate in the first year followed by nine years without pumping. The model runs were only varied in the rate of pumping extraction (total volume extracted during the year); all other
boundary conditions used inputs from 2003 such that any changes in simulated results are isolated to effects of pumping.

The geologic information used in the CVHM also includes the location of major faults for the Central Valley. This input has a substantial effect on the model, as seen in the “chopped off” cone of depression in Figure 21, caused by the Corning fault. The cone of depression follows the Corning fault line that is represented in the CVHM as a potential flow barrier (Faunt, 2009). A potential flow barrier does not necessarily block flow; it impedes flow. As shown in later figures, the cone of depression spreads to the west of the fault at a slower rate of decline than the east side of the fault thus playing a significant part in the decline of the water table on that side of the fault. The fault forces more water to be derived from the east side of the fault because of the impeded flow through the low transmissivity material of the fault.

Figure 20. Precipitation rates for California’s Central Valley 1962-2002;
Figure 21. Fault line potential flow barriers in CVHM and example of cone of propagation to east of the fault lines.

Model Scenarios

The model runs varied the pumping rates from 75,000 acre-ft/year to 600,000 acre-ft/year in 75,000 acre-ft increments. The pumping rates affect the Sacramento Valley in a variety of ways. The pumping is simulated as a constant extraction rate located at 39°30'4.16"N Latitude and 122° 3'40.50"W Longitude and is spread evenly throughout the year. This results in an extraction rate of 252,863 m³/day to correspond
with the length unit of meters and time unit of days used by the CVHM. The rate corresponds to 205 acre-ft/day of extraction or 75,000 acre-ft/year the smallest extraction rate used in the groundwater pumping scenarios. The other scenarios use the same rate but are up scaled using a multiplier of 2,3,4,5,6,7 or 8 depending on the scenario. The CVHM uses bi-monthly time steps and the model outputs hydraulic heads for every node in the grid, (432,180 nodes) every month for the 10-year simulation period, resulting in 51,861,600 head elevation values. To summarize these results in a format that is easily understood, hydraulic heads in each node of the upper model layer are averaged over the entire year. This is converted to drawdowns by subtracting head elevation output from the base model run without pumping from the different pumping scenarios. The base model is the exact same model excluding the pumping for water transfers.

The 51,861,600 simulated hydraulic head outputs from each of the eight pumping scenarios are processed using the python script developed for this thesis. The python script allows for parsing of the data into a water table elevation from the 10 layers of the model as well as averaging the heads over the 12 monthly outputs for each of the 10 years that the system was simulated. All water table drawdowns that were analyzed represent yearly averages. The information is outputted as a text file that is space delimited and can be inputted into an Excel spreadsheet to produce graphs, and allow formatting for input into GIS for spatially referenced outputs.

The starting rate used for the model was set at 75,000 acre-ft/year to simulate 15,000 acres of groundwater substitution, substituting groundwater when surface water allotments are curtailed, to irrigate fallowed fields. The amount of water needed to irrigate a typical rice field in the Sacramento Valley is approximately 5 acre/ft per year,
thus 15,000 acres would need 75,000 acre-ft/year to irrigate those lands. The pumping rate of 300,000 acre-ft/year is taken from Sacramento Valley Conjunctive Water Management Technical Investigation Modeling Report; this was the highest rate that was investigated in the report (Lawson et al., 2010). The report investigated the use of groundwater to supplement reservoir operations and surface water deliveries and modeled extraction rates up to 300,000 acre-feet/year. To investigate the spatial impact of even larger pumping for water transfers, this thesis examines pumping rates as high as 600,000 acre-ft/year.

The 75,000 acre-ft/year pumping rate primarily affects the first year on the east side of the fault line extending to Oroville, CA, with the west side of the fault being less affected. After 4 and 9 years of recovery from the end of pumping the aquifer decline stabilized between .1 to .4 feet of water table decline, Figure 22. All water table elevations are yearly averages to reflect the overall decline in water table elevation and the water table stabilizes to nearly .3 feet of the starting elevation in this scenario. The highest drawdown seen was approximately .5 feet in the vicinity of the pump.

Figure 23 shows the pumping impacts from 150,000 acre-ft/year. The cone of depression progresses much farther than the 75,000 acre-ft/year scenario extending the whole breadth of the valley with the recovery not rebounding as fully.

After four years of recovery the water table elevation still shows a focused cone of depression that ranges from .4ft to .8ft of drawdown. After nine years of recovery the aquifer recovers back to a water table elevation that is stable across the aquifer but that has declined from the original elevation. The decline of the the water table after nine years of recovery ranges between.1ft to .4ft.
Figure 22. Drawdown at 75,000 acre-ft/year after 1 year of pumping, 4 and 9 years of recovery.
Figure 23. Drawdown at 150,000 acre-ft/year after 1 year of pumping, 4 and 9 years of recovery.
The 225,000 acre-ft/year scenario’s output in Figure 24 illustrates the continued growth of the cone of depression from the previous models. This scenario indicates a larger, more pronounced decline that recovers back to between .5 and .8ft. This is the first scenario where the average water table does not recover in the area of the cone depression back down to the .1 to .4ft levels as was previously observed. The increased amount of water that is being extracted has not had time to recover to an aquifer-wide stabilized level. The water table decline does not reach its outermost extent at the end of pumping, but as shown in the 4th year of recovery, the drawdown continues to extend as the aquifer recovers. The nature of groundwater is to flow down gradient; therefore even if pumping is stopped the groundwater continues to flow in the direction of lowest gradient. This continues to move water from higher head areas to lower head areas extending the cone of depression but not increasing maximum drawdown.

The pumping rate of 300,000 acre-feet/year, as shown in Figure 25, demonstrates up to 2ft of decline in the vicinity of the well. By the 4th year of recovery water levels have recovered by .8ft to 1.2ft in the vicinity of the well. After a further five years the aquifer recovers more but the cone of depression still exists and the aquifer is continuing the process of returning to an equilibrium state. This scenario illustrates the propagation of the water table decline after the termination of pumping.

The 375,000 acre-ft/year pumping rate that is shown in Figure 26 is the first scenario where the cone of depression progresses to the west of the fault. The time to change the gradient enough to draw flow from the west is revealed in the time lag from the first year of pumping to the fifth. The time at which the water table is affected
Figure 24. Drawdown at 225,000 acre-ft/year after 1 year of pumping, 4 and 9 years of recovery.
Figure 25. Drawdown at 300,000 acre-ft/year after 1 year of pumping, 4 and 9 years of recovery.
Figure 26. Drawdown at 375,000 acre-ft/ after 1 year of pumping, 4 and 9 years of recovery.
the most on the west side of the fault comes three years after pumping is halted. This is shown in Figure 27.

The time for the cone of depression to reach the west side of the fault is due to the flow barrier caused by the fault. The groundwater flow must either flow through the irregular, low transmissivity material at the fault interface or under the fault through a different layer. The drawdown must be significant enough to effect gradients under the fault. At this pumping rate the maximum average annual decline ranges between 2.4-2.8 ft at the well and the Sacramento Valley as a whole could possibly see declines of 0.1 to 0.4 ft. Figure 28 shows results from the second highest rate scenario that was modeled at 525,000 acre-ft/year. At this rate the annual average drawdown around the well site is 2.8 to 3.2 ft. This rate produces much of the same effects as the final scenario at a pumping rate of 600,000 acre-ft/year shown in Figure 29.

The final scenario was the most extreme and had a maximum drawdown of 3.7 feet at the well site. The extent of drawdown of over 1.0 feet at 600,000 acre-ft/year pumping rate covers approximately 851 square miles as shown in Figure 30. This pumping rate is 2 times higher than other rates that have been investigated up to this time (Lawson, Bourez, & Bergfeld, 2010).

This pumping rate illustrates the potential for drawdowns to extend many miles from the source of pumping as well as the propensity of the decline to rebound gradually. Replenishing groundwater supplies in average water years takes many years as seen in Figure 31 in that the water table elevations at the end of the scenarios are still not recovered to the pre pumping levels.
Figure 27. Graph showing the time lag to max drawdown on the west side of the fault as well as the spatial reference.
Figure 28. Drawdown at 525,000 acre-ft/year after 1, 5 and 10 years. Pumping is stopped after first year with nine years of recovery
Figure 29. Drawdown at 600,000 acre-ft/year after 1, 5 and 10 years. Pumping is stopped after first year with nine years of recovery.
Figure 30. Extent of Drawdown of one foot or more after a year of pumping at 600,000 acre-feet/ year.

Recharge in the Sacramento Valley occurs through rainfall and stream/river interactions with the aquifer. The recharge is governed by groundwater flow which is dependent on transmissivity, water table gradients and the amount of storage that needs to
Figure 31. Graph showing drawdown were identified, as well as showing time needed for aquifer recovery
be replenished. The drawdown nine years after the pumping ceases at the well cell is still 1.2 feet. The decline, as shown in Figure 32, is extensive to the east of the pumping site and the fault. The influence of the well at this rate was approximately 1528 square miles with water table elevation declines ranging from as much as 3.7 feet to as little as .1 feet. As shown in Figure 4.15, at a distance of 22 miles east of the well site, the groundwater elevations are still recovering after 9 years. This illustrates the large timescales that this system needs to propagate a cone of depression as well as recovery from extraction.

The area of influence of groundwater pumping for water transfers can be very large even in average years of precipitation and recharge. If additional pumping for water transfers were included within the 10-year simulation, recovery times would be even longer. The drawdowns for the model at the high end of the extreme case of the 600,000 acre-ft/year scenario revealed an area that stretched from Red Bluff in the north to Sacramento in the south. While the effect on the water table farther than 20 miles away was under .4 feet the extent of the influence is large. This study indicates that the water table could decline from .6 feet to 3.7 feet on average per year of pumping.

After pumping is ceased, the long recovery of groundwater storage can be seen in Figure 33. Groundwater that is extracted by pumping but left to natural recharge processes produces the two different gradients shown in Figure 33. The recovery is calculated by the percent that the pumping scenario recovers from the maximum drawdown in that scenario.

Figure 33 illustrates the sharp decline during pumping and the slow rebound due to natural recharge and ground water flow as well as the percent of recovery for each pumping scenario.
Figure 32. Drawdowns 22 miles from well site.
Results

An unexpected finding of this investigation is the strong influence of the faults within the study area on the groundwater flow, as shown in Figure 34. The faults that are in the CVHM are treated as potential flow barriers. They impede flow but do not stop flow because they are areas of low transmissivity not a no-flow boundary. Faults are modeled as potential flow barriers because at the locus of faults there is a preponderance of fine-grained material that tend to block or reduce groundwater flow (Sweetkind,
Fault Line that most prominently effects drawdown

Belcher, Faunt, & Potter, 2004). Fault zones are fractured and with a core that has a low hydraulic conductivity they also tend to turn groundwater flow along their length due to their fractured nature (Sweetkind et al., 2004).

*Figure 34.* Fault line in model and the effect it has on the propagation of cone of depression.
This can be seen in Figures 22-30 where the cone of depression impacts the east side of the fault where the pump is located much faster than the part of the aquifer located to the west of the fault. There is potential for more study of the faults and aquifer testing on either side of the fault to verify the hydraulic conductivity of the fault core sediments.

Further results of this study are the length of time or lag from the end of pumping and to the highest drawdown and the use of a large-scale regional model for a smaller more local area. The length of time to maximum drawdown is due to the transmissivity, the distance from the well and storage. There are two sites which represent these variances well in Figure 35 and Figure 32. Figure 35 is a site to the west of the fault running through the research area and is an example of the effect of transmissivity on timing of drawdown propagation. Figure 32 demonstrates the effects of distance.

These outcomes illustrate the need to understand the system dynamics. Transmissivity and storage can greatly affect the local decline of water tables and how quickly they propagate. A large model, like the CVHM which uses a 1 mile by 1 mile grid, can simulate water table declines on the scale of the Sacramento Valley due to large scale pumping, but is not appropriate for pinpointing local-scale drawdowns at the acre scale. Future studies using the CVHM to simulate local effects could be implemented by refining the grid using the Local Grid Refinement (LGR) (Mehl & Hill, 2010) capability in MODFLOW to simulate sub regions in more detail. This would keep the local model linked to the larger model to propagate effects to neighboring areas without refining the whole CVHM. This approach would also allow the refinement of land use data, well
Figure 35. Measurement site two miles west of well site on the opposite side of fault line.
placement, representation of smaller streams, and other local scale inputs that an interest group may desire.

Conclusions

In conclusion, modeling of groundwater pumping for water transfers in the Sacramento Valley illustrates that large-scale pumping can have an effect on water table elevations over a large area and for an extended period of time compared to the time that it takes to extract groundwater. This area extended from Red Bluff, CA to Sacramento, CA and the whole breadth of the Valley. None of the pumping scenarios recover by more the 71% to the base run water table elevations illustrating the prolonged effect and recovery of large scale pumping endeavors. Furthermore, the potential influence of faults on groundwater flow was shown to localize effects of pumping and create drawdowns that reflect away from the fault, delaying the drawdown effects on the side of the fault opposite to that of the pumping. This can greatly change the simulated results both in terms of magnitude and direction of groundwater declines.
CHAPTER V

MODELING STREAM/AQUIFER INTERACTIONS COMPARED TO ANALYTICAL SOLUTIONS

Introduction

The interconnection between stream flows and groundwater aquifers in MODFLOW can be calculated using the stream flow routing package as leakage across the streambed (Prudic, Konikow, & Banta, 2004). In large-grid models, the flow lines from the vertical leakage of a stream/river to the horizontal flow of the groundwater is difficult to model due to the inability for the flow to turn from the vertical to horizontal as it would naturally within a finite difference cell. In a finite difference model, all interactions are node to node. Therefore, if the discretization is larger than the curvature of the flow line and the change from a vertical flow to a horizontal flow occurs within a single finite-difference cell, the calculated leakage may be inaccurate. In this situation, the model may need calibration of the streambed conductivities or the model grid refined to a size that will properly model the flow. To model stream/aquifer interactions, a properly refined three-dimensional grid is needed (Mehl & Hill, 2010), or the streambed conductivity must be calibrated. A discretization that closely matches the stream bed thickness enables the model to simulate the streambed more accurately without
interference from the resistance of the aquifer materials between the stream bed and the node in the cell. Simulation of stream-aquifer exchanges (flow between the streambed and cell node) often is done through calibration of a streambed conductance. Using a fixed streambed conductance to model the interaction between the stream and aquifer fails to account for the changing amount of material between the stream bed bottom to the cell node as the grid is refined both horizontally and vertically (Mehl & Hill, 2010).

A promising solution developed by Dr. Morel-Seytoux uses an analytical solution, which is grid dependent but useful for large grids and investigates 3 different geometries, as shown in Figure 36, coupled to MODFLOW to calculate the conductance (Morel-Seytoux, 2009). This thesis tests varying grid sizes against the conductance from the analytical solution called the “turning” factor to both verify the “turning” factor and to investigate discretizations that closely match the analytical solution, “turning” factor.

Further research was included on the effects of varying grid size outside of the stream bed resolution and including a variety of pumping rates to create a more-complicated flow field near the stream than initially proposed by Morel-Seytoux.

Model Setup

Three different geometries were evaluated; flat, rectangle, and trapezoid, as shown in Figure 36. The conductance developed by Morel-Seytoux (2009) is referred to as a “turning” factor and is dimensionless; therefore no length units are included because the lengths can be whatever lengths that a model is using, meters, feet, miles, etc. To model the turning factor the hydraulic conductivity (K) in all three directions, (x, y, z) is
Figure 36. Three different geometries used to model the stream cross-section, flat, rectangular, and trapezoidal. The flat diagram illustrates the Dx2D prerequisite needed for the “turning” factor. set to 1.0, and the size of the model, shown in Figure 37, where D, the aquifer depth, is equal to 10.

The head in the stream is set to 1 and the General Head Boundary is set to 0 with the hydraulic conductivity, K, also set to 1. This system is designed to match the turning factor inputs and insures that any variances are due to grid size. The aquifer size to the right of the stream (the area between the stream edge and the General Head Boundary on the right) was held constant shown in Figure 37 to fit into the requirements of the aquifer dimensions set forth by Morel-Seytoux (2009). This distance can vary in
size as the river geometry changes but for this investigation, D is 10.0 for all scenarios.

Figure 38 is a screenshot of a 25 by 10 aquifer discretization applied to a rectangular stream geometry. It shows the placement of the general head boundary. The interior black line is the aquifer extent; cells outside of this and the river reach are not modeled.

**Primary “Turning” Factor Scenarios**

The first model cases simulated a flat river with no penetration into the aquifer to determine how different grid refinements approached the “turning” factor calculated conductance of 0.305. The histogram in Figure 39 illustrates the approach to the analytical solution through the use of more refined discretizations. At the 84 x 40 discretization (80 columns by 40 rows for the 2DxD portion), the MODFLOW model is...
Figure 38. MODFLOW model setup 20x10 cells representing aquifer as well as delineation of model boundary conditions.

within 1.67% of the analytical solution. The refinement for the 2D x D portion of the model is a 320 times refinement from the analytical solution which would be essentially a 1x1 model that is predetermined by Morel-Seytoux’s parameters. The flat geometry was then modeled at many different wetted perimeters.

Figure 40 illustrates the convergence to the analytical solution as the MODFLOW discretization is refined. The flat river geometry characteristics of interest converge at the 80x40 discretization. All tested discretizations after this point follow the same line as Morel-Seytoux's analytic solution. The graph in Figure 40 indicates as the discretization becomes small enough to model the stream bed conductance and stream reach more accurately, the conductance or “turning” factor is solved for with a low percentage error as mentioned previously.
The second scenario modeled a rectangular stream geometry that penetrates into the aquifer allowing for seepage through more than one face of the streambed as shown in Figure 38. For all of the geometries the head was maintained at 1.0 throughout the extent of the stream wetted perimeter. As before, simulated results at the 80x40 discretization are close to the analytical solution, but with inconsistencies in the data that the flat river geometry did not have. The inconsistencies in the rectangular models compared to the flat models are attributed to the geometry of the stream not matching the grid as well as in the flat trials.

Figure 39. A histogram of convergence of flow to the “turning” factor flow by refining the grid discretization.
Figure 40. Flow through the model at different discretizations and differing normalized wetted perimeter, (Wetted Perimeter/Aquifer Depth), compared to flow using “turning” factor for flat stream geometry.

At a discretization of 400 x 160 the MODFLOW model converges to an answer that matches almost identically with the finest grid that was applied (1600x640) as shown in Figure 41. In the rectangular trials the penetration of the stream and the corner of the stream are more difficult to model due to the stream not fitting the grid well as shown in Figure 42. Therefore, the rectangular grid can be modeled with the same results as the “turning” factor at approximately a 51,200 cells in place of the 1x1 cell using the “turning” factor.
Figure 41. Flow through the model at different discretizations and differing normalized wetted perimeter, (Wetted Perimeter/Aquifer Depth), compared to flow using “turning” factor for rectangular stream geometry.

The third geometry that was investigated was a trapezoid, as shown in Table 1 and Figure 43. This shape more closely resembles the sloped sides of a natural channel but was also found to be the most difficult to model. The difficulty in modeling the trapezoidal shape stems from the number of cells needed to represent the streambed correctly. It was found that the trapezoidal geometry was modeled very well at the 448x160 discretization and above. The difference between the two highest discretizations was minimal but measurable. The percent error found between the “turning” factor analytical solution and the modeled “turning” factor are low with an error of 1% to 1.4%
Figure 42. The parts of the stream reach that are hard to model at large discretizations due to stream geometry not matching well with grid used. Higher discretization decreases the parts that of a stream geometry that do not match the grid and reduces the error.

for the larger wetted perimeters, Table 1. This error is possibly due to the convergence in calculating the “turning” factor or poor alignment even at a fine discretization. The trapezoid geometry provides the best match to a natural shape but takes more computing power to model. The larger amount of computing power is due to the higher discretization needed to model it effectively.

The three geometries tested all converge effectively to the “turning” factor that is proposed by Hubert Morel-Seytoux, (Morel-Seytoux, 2009). Comparison of these results demonstrates that in a finite difference model, more complex stream geometries require finer grids to accurately simulate the interaction between stream and aquifer.
Table 1

*The Percent Error in Flow Between the Highest Discretization, Model and the “Turning” Factor. A Larger Discretization Trial Without a Percent Error Calculation for Reference to See Convergence Is Also Shown.*

<table>
<thead>
<tr>
<th>Turning Factor-Model</th>
<th>Turning Factor-Model</th>
<th>Turning Factor Hubert</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.423</td>
<td>0.4232</td>
<td>0.4292</td>
<td>1.4%</td>
</tr>
<tr>
<td>0.4162</td>
<td>0.4172</td>
<td>0.4219</td>
<td>1.1%</td>
</tr>
<tr>
<td>0.4047</td>
<td>0.406</td>
<td>0.4082</td>
<td>0.5%</td>
</tr>
<tr>
<td>0.3971</td>
<td>0.3979</td>
<td>0.3984</td>
<td>0.1%</td>
</tr>
<tr>
<td>0.3882</td>
<td>0.3887</td>
<td>0.3891</td>
<td>0.1%</td>
</tr>
<tr>
<td>0.3779</td>
<td>0.3794</td>
<td>0.3802</td>
<td>0.2%</td>
</tr>
<tr>
<td>0.3697</td>
<td>0.3701</td>
<td>0.3690</td>
<td>-0.3%</td>
</tr>
<tr>
<td>0.3612</td>
<td>0.3605</td>
<td>0.3610</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

The “turning” factor effectively calculates conductance, with the large grid specified for the stream geometries considered, compared to highly discretized models. (Morel-Seytoux, 2009).

Additional “Turning” Factor Scenarios

After the scenarios of differing geometries were investigated other stresses on the system were included by incorporating pumping at varying distances as well as varying grid size in the cell adjacent to the 2DxD cell specified by Morel-Seytoux. Models are often built with a uniform grid that may not meet the requirement of the first cell being 2D from the stream cell. The first test was to vary the size of the cell adjacent to the 2D aquifer cell. As shown in Figure 44 the varied size of the adjacent cell did not effect of the results.
Figure 43. Flow through the model at different discretizations and differing normalized wetted perimeter, (Wetted Perimeter/Aquifer Depth), compared to flow using “turning” factor for trapezoidal stream geometry.

When the cell adjacent to the 2DxD cell, Figure 37, varies in size, Figure 44, the “turning” factor still remain a valid interpretation of streambed conductance.

Figure 45 is a comparison between the 2 cell model using the “turning” factor as streambed conductance in the model and the same setup ran without the “turning” factor in a fine grid 100x400 cells. The pumps were placed at intervals as shown in Figure 47 to assess the effects of pumping not located at the cell center in the large grid compared to the fine grid used without the “turning” factor. Secondly, pumping was added to the model to test the effects of a competing sink on a system modeled using the “turning” factor for the streambed conductance.
Figure 44. Flow modeled through an additional cell outside of the 2D away parameter that varies size along same gradient to investigate the “turning” factors use in a grid that does not match 2D away grid but hold the 2D parameter at the stream the same.

<table>
<thead>
<tr>
<th>Wqd</th>
<th>Hubert Flow</th>
<th>Ratio</th>
<th>Width Bigger</th>
<th>Head @GHB</th>
<th>Conductance</th>
<th>Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.3422</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>21</td>
<td>-2.8744</td>
<td>0.95238095</td>
<td>0.3422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>42</td>
<td>-5.03034</td>
<td>0.47619048</td>
<td>0.3422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>46.2</td>
<td>-5.461512</td>
<td>0.432900043</td>
<td>0.3422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>52.5</td>
<td>-6.10827</td>
<td>0.38095238</td>
<td>0.3422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>63</td>
<td>-7.1862</td>
<td>0.31746032</td>
<td>0.3422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.75</td>
<td>73.5</td>
<td>-8.26413</td>
<td>0.27210884</td>
<td>0.3422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>84</td>
<td>-9.34206</td>
<td>0.23809524</td>
<td>0.3422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>105</td>
<td>-11.49792</td>
<td>0.19047619</td>
<td>0.3422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>126</td>
<td>-13.65378</td>
<td>0.15873016</td>
<td>0.3422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>210</td>
<td>-22.27722</td>
<td>0.09552381</td>
<td>0.3422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>420</td>
<td>-43.83582</td>
<td>0.04761905</td>
<td>0.3422</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 45. Varying well placement in well adjacent to stream cell and comparison of accuracy.

<table>
<thead>
<tr>
<th>Wqd</th>
<th>“Turning” Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.3422</td>
</tr>
</tbody>
</table>

Well Placement Variations-.2 Pumping

<table>
<thead>
<tr>
<th>Ratio Placement</th>
<th>Flow-“Turning” Factor</th>
<th>Flow Grid-100x400</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>0.4614</td>
<td>0.4795</td>
<td>3.92%</td>
</tr>
<tr>
<td>0.25</td>
<td>0.4614</td>
<td>0.4738</td>
<td>2.69%</td>
</tr>
<tr>
<td>0.5</td>
<td>0.4614</td>
<td>0.4613</td>
<td>0.02%</td>
</tr>
<tr>
<td>0.75</td>
<td>0.4614</td>
<td>0.4489</td>
<td>2.71%</td>
</tr>
<tr>
<td>0.87</td>
<td>0.4614</td>
<td>0.4432</td>
<td>3.94%</td>
</tr>
<tr>
<td>1.12</td>
<td>0.4137</td>
<td>0.4318</td>
<td>4.4%</td>
</tr>
<tr>
<td>1.25</td>
<td>0.4137</td>
<td>0.425</td>
<td>2.7%</td>
</tr>
<tr>
<td>1.5</td>
<td>0.4137</td>
<td>0.4137</td>
<td>0.0%</td>
</tr>
<tr>
<td>1.75</td>
<td>0.4137</td>
<td>0.4023</td>
<td>2.8%</td>
</tr>
<tr>
<td>1.87</td>
<td>0.4137</td>
<td>0.3955</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

Figures 46 and 47 illustrate the impacts of both distance away from center and pumping rate on the simulated stream-aquifer exchanges. The error introduced is caused by the pump not being at the cell center. The effect of the error due to the location of the
pumping is increased as the distance between the center of the well and the node increases.

In a finite difference model all inputs in a cell are modeled as if they were at the node or center of that cell. Therefore, the input will always be modeled at the center of the cell no matter where it is in actual space in the cell. This can lead to inaccuracies when using large cell sizes because the spatial variability within a cell is lost. Figure 47 shows accurate results where the pumps are located at the nodes. This indicates that the error introduced into the models with the “turning” factor are not due to the “turning” factor itself but are indicative of modeling with large discretizations.

Conductance is calculated as shown in Figure 48. A comparison of methods used to calculate streambed conductances in a rectangular channel was performed using streambed conductance calculated as shown in Figure 49 with L not normalized by Wqd and with it normalized. The two different grid-calculated streambed conductances were compared to the “turning” factor of Morel-Seytoux (2009).
Pumping was included at a 25% offset from the node to investigate how all of the methods compared in a more complex system in these scenarios. This test looked at five different wetted perimeters in three different model setups; three large discretization models, grid calculated and “turning” factor models, and one finely discretized model as a control. The three large discretized models differ in the streambed conductance, one using the “turning” factor and the others using the grid calculated methods. The results from these scenarios are shown in Figure 50 and indicate the relative error using the “turning” factor was consistent at 2.04 to 2.40% compared to the fine grid model, whereas the grid calculated non-normalized method error varied greatly from 1 to 21% error. The grid calculated method multiplied by the normalized wetted perimeter showed a relative error ranging from .88% to 4%. This error is very close in these scenarios to the

Figure 47. “Turning” factor flow with .1 pumping compared to fine discretization.
turning factor but as the wetted perimeter compared to aquifer depth increases the error trended to increase. The grid calculated methods were developed by Dr. Steffen Mehl and Kyle Morgado to compare methods using grid size to calculate the needed streambed conductance.

The “turning” factor modeled the streambed conductance regardless of the wetted perimeter whereas the grid calculated method accurately simulated the large wetted perimeters but showed large errors for smaller wetted perimeters and the normalized grid calculated conductance was within a few percent error of the “turning” factor for the specific models in this investigation.

Results

Using the “turning” factor for streambed conductance in regional scale models has the potential to allow a larger grid finite difference model to accurately simulate
stream/aquifer interactions. The scenarios were simulated using the parameters set forth by Morel-Seytoux (2009) but incorporation of the “turning” factor into other models was not simulated. For the scenarios investigated in this thesis, the “turning” factor performed well, including situations with pumping and more complicated flow fields than originally considered by Morel-Seytoux (2009). The validation that the “turning” factor can possibly be a tool to help simplify and better model streambed conductance was demonstrated through simulations showing it produces outputs that are on par with a highly discretized model.

**Figure 49.** Grid calculated streambed conductance.
<table>
<thead>
<tr>
<th>Wqd, (Wetted Perimeter/Aquifer Depth)</th>
<th>&quot;Turning&quot; Factor Resistance</th>
<th>Based on Grid Resistance</th>
<th>Based on Grid Normalized by Wqd</th>
<th>&quot;Turning&quot; Factor Conductance</th>
<th>Streambed Conductance-Based on Grid</th>
<th>Streambed Conductance-Based on Grid-Normalized by Wqd</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25154</td>
<td>14.45530146</td>
<td>13.05076165</td>
<td>16.76279418</td>
<td>0.4329</td>
<td>0.479489256</td>
<td>0.373308885</td>
</tr>
<tr>
<td>1.09</td>
<td>12.98205525</td>
<td>12.73037706</td>
<td>14.27702372</td>
<td>0.423661731</td>
<td>0.432037478</td>
<td>0.385234353</td>
</tr>
<tr>
<td>1.04312</td>
<td>12.36099919</td>
<td>12.65534237</td>
<td>13.54220333</td>
<td>0.42194321</td>
<td>0.412126345</td>
<td>0.385136737</td>
</tr>
<tr>
<td>0.95592</td>
<td>11.42324514</td>
<td>12.49994826</td>
<td>12.25059226</td>
<td>0.418413452</td>
<td>0.382369583</td>
<td>0.390152565</td>
</tr>
<tr>
<td>0.8765</td>
<td>10.66351575</td>
<td>12.36582144</td>
<td>11.1823674</td>
<td>0.415221893</td>
<td>0.354869268</td>
<td>0.394689383</td>
</tr>
<tr>
<td>0.8068</td>
<td>9.884604077</td>
<td>12.24906711</td>
<td>10.1161584</td>
<td>0.408162646</td>
<td>0.329372022</td>
<td>0.398819079</td>
</tr>
<tr>
<td>0.7144</td>
<td>8.781895584</td>
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<td>0.130158275</td>
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<table>
<thead>
<tr>
<th>&quot;Turning&quot; Factor Flow</th>
<th>Based on Grid Flow</th>
<th>Based on Grid Flow-Normalized with Wqd</th>
<th>Fine Grid 160x400 Fow</th>
<th>Hubert’s Flux</th>
<th>Based on Grid Conductance Flux</th>
<th>Based on Grid Conductance Flux-Normalized with Wqd</th>
</tr>
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<tr>
<td>0.5482</td>
<td>0.5545</td>
<td>0.5382</td>
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<td>-1.09%</td>
<td>-4.00%</td>
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<td>-8%</td>
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<td>0.88%</td>
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Figure 50. Three methods of streambed conductance.

Table comparing “turning” factor streambed conductance, conductance calculated from grid size/wetted perimeter, conductance calculated from grid size/wetted perimeter*Wqd and using a fine grid. . Pumping and 25% offset of well From node.-

The “turning” factor’s ability to work within an existing grid is the main application hurdle that was found during this thesis. The “turning” factor was developed for one layer models. Further investigation is needed on the “turning” factor’s use for
multiple layer models to make the incorporation of the “turning” factor in complex multi-layer models. Additional investigation is needed to incorporate the “turning” factor into different models that do not meet the grid requirements set by Morel-Seytoux (2009) and how deviations from the requirements affect the use of the “turning” factor.
CHAPTER VI

CONCLUSIONS AND SUGGESTIONS

FOR FUTURE WORK

Conclusions

This thesis illustrates the use of regional scale models to predict the temporal and spatial change in water table elevation and aquifer storage along with new methods to further refine regional scale models for simulating stream aquifer interactions. These two areas of investigation both make use of regional models; one to simulate effects of pumping on a region, the other to validate the possibility of new methods of modeling small features, streams/creeks, in a large grid, (regional model). The two come together to use regional models for investigations of aquifer dynamics, storage depletion, and water table elevations, and to investigate ways to improve regional models.

The CVHM identifies water table declines in the Sacramento Valley and illustrates the effects of large-scale pumping but makes it difficult to pinpoint drawdowns at scales less than one mile. Modeling groundwater pumping for water transfers in the Sacramento Valley illustrates that large-scale pumping can affect water table elevations over a large area. The drawdown of the water table over a large area results in large amounts of water withdrawn from the aquifer and the inability of the aquifer to rebound back to pre-pumping conditions in the nine years of modeled recovery. The models also show a long period of time needed to recharge the aquifer system when recharged.
through natural processes. This indicates that if large scale pumping occurs, efforts to understand how to recharge the aquifer more quickly may need to be undertaken to augment the natural recharge rate.

The role of faults on groundwater flow in the valley was shown to have a great effect on propagation of the cone of depression and the direction that the cone propagates. The influence of faults on groundwater flow was shown to localize effects of pumping and to orient it away from the fault. This changes the simulated water table declines and influences groundwater decline disproportionally on the pumping side of the fault.

This thesis also demonstrated that the “turning” factor can be a successful technique to help simplify and better model streambed conductance without the use of a highly discretized model. The ability of the “turning” factor to incorporate accurate stream bed conductances into large scale models, rather than using highly discretized models (thus saving on computing time), is a very useful and powerful tool. While the “turning” factor works well when the grid size requirements of Morel-Seytoux (2009) are satisfied, models that do not fit these criteria would be more typical in practice. Understanding how to use the “turning” factor in a finite difference grid that does not match the Morel-Seytoux (2009) requirements is of great interest. The scenarios simulated in this study with the “turning” factor were not refined to see the effects of violating the grid size requirements. Including grid refinement in three dimensions with the “turning” factor to calculate streambed conductance within a model is important to make the “turning” factor a useful tool in modeling with practical finite difference grids.
Further Work

Future studies using the CVHM to include more detail locally could be implemented by refining the grid using the Local Grid Refinement (LGR) (Mehl & Hill, 2010) capability in MODFLOW to simulate a sub region more accurately. This would keep the local model linked to the larger model to propagate effects to neighboring areas without refining the whole CVHM. This approach would also allow the refinement of land use data, well placement, representation of smaller streams, and other local scale inputs that an area of interest may need. Also investigating different scenarios with climate variability, fallowing, and pumping season variability would incorporate multiple scenarios into factors that can exacerbate the effects of large scale pumping.

Additional investigation is needed on strategies for incorporating the “turning” factor into different models that do not meet the grid size requirements of Morel-Seytoux (2009) and how this violation affects the simulated results. Furthermore, investigation is needed on the “turning” factor’s use for multiple layer models to. These tests are needed to verify ways to incorporate the “turning” factor into practical finite difference models to help to obtain more accurate stream impacts.
REFERENCES
REFERENCES


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APPENDIX A
PYTHON POST PROCESSOR

Python Post Process Tool Flow Cart

- Input MODFLOW headsout.txt file
- Extract 1 year of data-10 layers, 12 time steps
- Format Data into Single Column
- Extract Single Timestep-10 layers
  Stack layers in an array to find maximum head out of all layers,
  Water Table Elevation
- Do this for all 12 time steps
- Stack all 12 time steps in single columns creating an array 43218 x 12
- Average the water table elevations for the Year creating new array 43218x1
  of average water table elevation for the year.
- Stack all 10 years of model run into an array 43218x10.
- Save array as .csv file to be opened in excel and joined into GIS for both
  graphical and map view outputs
```python
import numpy as np
import math
import sv
import os

textfile='C:\Users\kmorgado\Desktop\head_start_2003.txt'

layerheight=3277
layer=19
header=9
timesteps=12
layerWOHeader=layerheight-header
col=1
years=10
fname=textfile

objectID=np.reshape(np.array(range(col,(layerWOHeader+col))),(layerWOHeader,col))
objectIDall=np.reshape(np.array(range(col,(layerWOHeader+col))),(layerWOHeader,col))

for k in range(0,years):
    pagesize=4749200
    size=os.path.getsize(fname)
    f=open(fname)
    pos=k*pagesize
    f.seek(pos)
    input=np.asarray(f.read(pagesize).split())

    for i in range(9,12):
        start=(layerheight*layers)+i
        inputF=np.reshape(input[(start:start+layerheight*layers),(layerheight,layers)],order='F')
        y=np.reshape(np.max(inputF[header:layerheight].astype('float'),axis=1),(layerWOHeader,col))
        output=np.hstack((objectID,y))

    smean=np.reshape(np.mean(np.delete(objectID,0,col),axis=1),(layerWOHeader,col))
    outputall=np.hstack((objectIDall,smean))

outputfinal=np.delete(objectIDall,0,col)
np.savetxt('C:\Users\kmorgado\Desktop\AnnualBase.txt',outputfinal,fmt='%.8e') # Save output as text file
```