MODELING ARTIFICIAL GROUNDWATER RECHARGE IN THE
SANTA ROSA CREEK WATERSHED

A Thesis
presented to
the Faculty of California Polytechnic State University,
San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Civil and Environmental Engineering

by
Alexander John Murray

June 2020
COMMITTEE MEMBERSHIP

TITLE: Modeling Artificial Groundwater Recharge in the Santa Rosa Creek Watershed

AUTHOR: Alexander John Murray

DATE SUBMITTED: June 2020

COMMITTEE CHAIR: Misgana Muleta, Ph.D., PE., D.WRE
Professor of Civil and Environmental Engineering

COMMITTEE MEMBER: Rebekah Oulton, Ph.D., PE.,
Associate Professor of Civil and Environmental Engineering

COMMITTEE MEMBER: Aleksandra Wydzga, PH,
Senior Hydrologist at Creek Lands Conservation and
Adjunct Faculty at California Polytechnic State University, San Luis Obispo
The Santa Rosa Creek Watershed is an approximately 48 mi² large watershed located on the central coast of California. This watershed drains to the Pacific Ocean through Santa Rosa Creek as it passes through agricultural land and the town of Cambria. Historically the groundwater within the Santa Rosa Creek Watershed has been used for irrigation, municipal and domestic uses, and the creek is critical habitat steelhead trout. During dry years, there is less water for all uses. When low groundwater levels occur, water can be drawn out of the creek and into the soil, drying out steelhead habitat. Seven agricultural operators within the Santa Rosa Creek Watershed are working with a local non-profit to improve sustainability of the aquifer through artificial groundwater recharge. One of these projects includes the use of a recharge basin. This study was conducted to understand the impacts of that recharge basin on the groundwater surrounding it as well as to evaluate the site’s potential for other recharge methods. The groundwater within the site of interest was modeled using GMS to calculate head values, to determine flow directions, and to determine timings. Three different hydrogeologic layers were used to simulate an upper unconfined zone, a clay confining layer, and a confined zone. The model was calibrated to known groundwater head values throughout the site. ArcMap was used to organize and preprocess data that went into the GMS model. Elevation, hydrologic soil characteristics, boundary heads, recharge rates, evapotranspiration rates, and well locations and pumping rates datasets were all preprocessed and imported into GMS. The model showed that the water from the recharge basin does not percolate into the underlying groundwater aquifer, but it flows out of the upper unconfined layer and into the creek over time. This is caused primarily by a low hydrologic conductivity confined aquifer in the northern section of the site as well as a confining clay layer underneath the unconfined top layer. According to the model, the site may not be feasible for artificial groundwater recharge in the northern portion, but there is potential for recharge in the southern area. Further data collection could improve the model to support or dispute these findings.
ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Misgana Muleta, for helping me find a project I was interested in and supporting me throughout the process. He assisted me along every step of the way. I am also thankful for my committee members, Dr. Rebekah Oulton and Aleksandra Wyzdga. Dr. Oulton was instrumental throughout my time at Cal Poly, and she has assisted me greatly in my studies. Without Aleksandra Wyzdga and her non-profit, this project would not be possible, so thank you as well for creating this opportunity.

Lastly, I want to thank everyone else in my life who has supported me throughout this experience. My friends encouraged and supported me throughout college and my family has always given me the opportunities I needed in life. I am grateful for everything they have done.
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CHAPTER 1: Introduction

Groundwater is a vital resource around the world for drinking, agricultural, domestic, and various other uses. Groundwater is obtained by extraction from underground aquifers with wells. In California, groundwater accounts for about 38% of the state's water supply in normal years and at least 46% in dry years (DWR, 2014). This heavy reliance on groundwater, especially by the agriculture sector, has caused widespread adverse impacts such as land subsidence, seawater intrusion, and loss of groundwater supplies in California and many other places (USGS, 2019).

The undesirable impacts of groundwater overuse become severe in times of drought (DWR, 2016). Between 2011 and 2016, for example, California experienced a drought that deepened the reliance on groundwater, causing significant overdraft. During the drought, 90% of groundwater wells in the state experienced a 3–15 meter (m) drop in water levels, and 8% of wells suffered drops of more than 15 m (DWR, 2016). California adopted the Sustainable Groundwater Management Act (SGMA) in 2016 to limit groundwater overdrafts and the subsequent adverse impacts. SGMA requires the development and implementation of Groundwater Sustainability Plans (GSPs) to properly manage the state’s groundwater resources effectively by 2040 (DWR, 2020).

Figure 1 shows typical characteristics of a groundwater system. Water can be drawn into an aquifer from surface waters such as creeks and streams, or vice versa. If aquifer levels drop too far because of overconsumption or a drought, well owners can runout of water for drinking and sanitation, farmers might not have enough water for irrigation, and rivers and streams may run dry from not having groundwater flowing into them.
In recent years, sustainable management of groundwater basins, for example through artificial groundwater recharges, has become a focus. Recharge basins, injection wells, flooding, and other methods are potential ways to increase groundwater levels (Todd & Mays, 2005). These methods work by artificially introducing water to groundwater aquifers with the expectations that the recharges will offset the drawdown from pumping. When attempting to implement artificial recharge there are many questions that need to be answered including: 1) what is the most effective method of recharge for the aquifer in question? 2) which recharge site are better? 3) will a proposed recharge site and method provide the anticipated benefits? One way these and many other questions can be answered is by developing a groundwater model that represents the groundwater system of interest and “testing out” different recharge options within this model.

Source: USGS (2020).

Figure 1: Wells can alter the natural flow of water by taking too much out of the system.
The objective of this study is to develop a groundwater model for a basin near Cambria, CA in the Santa Rosa Creek Watershed to analyze the impacts of an existing recharge basin as well as to evaluate potential for other methods of recharges.

1.1 Background

The area of interest for this study is located on a lemon and avocado farm that lies in the middle reach of the Santa Rosa Creek (SRC) Watershed and Groundwater Basin, specifically the Lower Santa Rosa Creek Sub Watershed (Figure 2). This area is just outside of Cambria, CA. The owner relies on groundwater under their land for irrigation and domestic uses, and they are actively attempting to recharge the groundwater for the benefit of both agricultural and environmental purposes. The Santa Rosa Creek nearby the farmer’s property relies on groundwater in the watershed as a source of flow in the dryer, summer months. When the groundwater levels are lowered substantially, for example during an extended drought, there could be less water for the farmer to use and less water in the creek, potentially harming the ecosystem.
1.1.1 Santa Rosa Creek Watershed

The Santa Rosa Creek Watershed is a source of water for farmers and ecosystems alike. The watershed is in the northern coastal area of San Luis Obispo County. The watershed limits to the east is the Santa Lucia Mountain Range and to the west, the Pacific Ocean (Upper Salinas-Las Tablas Resource Conservation District, 2020). The watershed is 48 mi² large and characterized by steep hillslopes, shallow soils, sparse shrubs, with agricultural areas and the town of Cambria near the coast as can be seen in Figure 3 (Stillwater Sciences, Central Coast Salmon Enhancement, and Greenspace – The Cambria Land Trust, 2012).
The area modeled within the watershed for this study lies along Santa Rosa Creek Road and is 126.2 acres large. The model is bounded by hills to the north and the Santa Rosa Creek to the south (Figure 4). The east and west boundaries were determined by the hills on the northeast and the northwest, and extensions of the hills on the southeast and the southwest. The area has moderate hillslopes in the northern areas but flattens out throughout the middle to southern areas. These lower areas are used for agricultural purposes as well as the road that passing through. There is an ephemeral waterway on the northern side of the site that runs through the agricultural land. This site is referred to as the farm site throughout this study.
1.1.2 Agriculture

Throughout the Santa Rosa Creek Watershed, there are plenty of crop farms. There is a wide variety of crop types, but the agriculture is dominated by avocados, which constitutes 50% of all crops, and hay which is 27% of all crops (USDA, 2020). Avocados and hay are particularly high-water use crops, requiring 827 mm/yr and 1078 mm/yr of water in the California Central Coast during a typical rainfall year (Cal Poly SLO, 2020). These water intensive crops put the groundwater basin under further strain to meet the demand.

1.1.3 Creek Habitat

The Santa Rosa Creek is a designated critical habitat for steelhead trout, *Oncorhynchus mykiss irideus* (Department of Commerce: NOAA, 2005). The steelhead found in the watershed are within the South-Central California Coast Distinct Population
Segment, which is listed as threatened under the federal Endangered Species Act (NOAA, 2020). It is important that there is enough water in the Santa Rosa Creek during times of low precipitation for the steelhead to survive. The water during these times comes from groundwater, and with groundwater pumping for farming and domestic uses, creek flows could be limited particularly during droughts. Artificial recharge can help sustain the instream flows needed for ecosystem health during low flow season.

1.2 Previous Work

In 1998, the USGS, conducted a study of the basin hydrogeology and water quality of the Santa Rosa Creek and Simeon Creek basins (Yates & Van Konyenburg, 1998). This report documented “the results of a 3-year study of ground-water resources in the Santa Rosa and the San Simeon Creek groundwater basins. Hydrogeology and water quality were the main points of interest of this report, and water budgets were developed. Many field measurements were taken, and models were created for the two groundwater basins.

In 2012, Stillwater Sciences, Central Coast Salmon Enhancement, and Greenspace worked together to create the Santa Rosa Creek Watershed Management Plan (2012). This plan was developed for the California Department of Fish & Game, in fulfillment of their Fisheries Restoration Grant Program. The plan describes the historical watershed conditions, assesses physical and biological conditions, determines, and prioritizes factors impacting the steelhead population and recommends actions to be taken to improve the overall watershed habitat.

Cleath-Harris Geologists produced a technical memorandum of the Middle Santa Rosa Creek Valley Watershed Hydrogeology of the Middle Reach Santa Rosa Creek Valley for Creek Lands Conservation (formerly called Central Coast Salmon Enhancement) (Cleath, 2019). The report used various data sources and investigations to provide a “hydrogeologic characterization of the middle reach of Santa Rosa Creek".
Included in this characterization “is a description of the basin sediments and configuration, aquifer parameters, and a discussion of factors to be considered in groundwater recharge enhancement” (Cleath, 2019).

Direct-push exploratory boreholes were drilled at the farm site along the middle of Santa Rosa Creek Watershed (Malama, Solum, & Nicholson, 2019) to understand the soil composition at and to evaluate percolation associated with proposed artificial groundwater recharge projects on the site. The key finding of the Malama (2019) study was that percolation methods for recharge at the site “would be challenging due to the presence of the near-surface low permeability subsurface unit” (Malama, Solum, & Nicholson, 2019), indicating that passive artificial groundwater recharge may not be possible due to a confining layer. In May 2020, Creek Lands Conservation hydrologists created cross-sections of the site based on these soil cores and a seismic survey done by Dr. John Jasbinack from Cal Poly San Luis Obispo (Figures 5, 6, and 7).
Figure 5: Location of cross-sections at the farm site. Source: Creek Lands Conservation (2020).
In a related on-going study, a coupled surface and groundwater model of the entire Santa Rosa Creek Watershed is being developed (Muleta, 2020). Dr. Muleta is
working on the model in coordination with Creek Lands Conservation to understand how/if artificial groundwater recharge is helping the watershed in regard to streamflow in the dryer seasons for steelhead trout and also groundwater levels for famers in the watershed. The surface water model is being modeled using the Soil and Water Assessment Tool (SWAT), and the groundwater model is being created on GMS. Many of the inputs for this study come from Dr. Muleta’s model. Dr. Muleta’s groundwater model is being created with 30 meter (m) by 30 m grid cells with 2 vertical layers. The grids are made at this resolution so that the whole watershed can be modeled without it becoming too encumbered computationally. The top layer in the groundwater model is an unconfined layer and the bottom layer is a potentially water-bearing confined layer. The model created in this study is much smaller in extent but detailed in resolution compared to Dr. Muleta’s model.

1.3 Purpose and Objectives

The purpose of this study is very similar to Dr. Muleta’s modeling study, but on a smaller, more defined scale. The purpose was to model and understand the effects of an existing artificial groundwater recharge basin at the farm site and further evaluate potential for other artificial groundwater recharge methods on the property. The hope is that the existing recharge basin is replenishing the farmer’s groundwater resources, and potentially providing flow to the Santa Rosa Creek, which is a habitat for the steelhead trout. This study was done on a small portion of the Santa Rosa Creek Groundwater Basin to understand the local impacts and benefits of the recharge basin and other recharge options with the goal that more artificial recharge will be implemented on the property and at other sites in the groundwater basin.

Models of groundwater basins can be used to compare different methods of recharge in an area to see what would work best. This allows for informed decisions to be made for groundwater management. This study analyzed the benefits of the existing
artificial groundwater recharge basin at the farm site. This was done by creating a granular model with 3 layers and 2 m horizontal grid resolution of the existing area and conditions. The reason for creating the granular model is because Dr. Muleta’s 30m resolution, watershed wide, model is not detailed enough to characterize how the area around the existing recharge basin responds to the recharge. Also, this study will be used by Dr. Muleta to see if his 30 m resolution model results will be similar to the 2 m resolution model and will be used to help to verify his model.

ArcMap 10.6 and GMS 10.4 were used to create this model. ArcMap is an Ersi software that helps to display and explore spatial data sets and also to create and edit data sets (Ersi, 2019). GMS is a proprietary software that supports MODFLOW, a commonly used groundwater modeling software package (Aquaveo, LLC, 2019). GMS requires many inputs to set-up groundwater model, and ArcMap was used to prepare many of these inputs.
CHAPTER 2: Literature Review

2.1 Artificial Groundwater Recharge

One way to combat overdrafts and low groundwater levels is through artificial groundwater recharge. Artificial recharge has been defined as “augmenting the natural movement of surface water into underground formations by some method of construction, by spreading of water, or by artificially changing natural conditions” (Todd & Mays, 2005). The artificial groundwater recharge method assessed in this study is the recharge basin method because there is already a recharge basin in-place at the farm site. This method and others are depicted in Figure 8.

![Various artificial groundwater recharge methods](image)

Figure 8: Various artificial groundwater recharge methods (a) surface basin, (b) excavated basin, (c) trench, (d) shaft well, (e) aquifer well. Source: Bouwer (1999).

2.2.1 Recharge Basin

The recharge basin method is a common and widespread method of artificial recharge. Recharge basins are pond-like areas where water drains to and can then percolate into the underlying aquifer. The basins are formed either by excavation or building dikes or levees (Todd & Mays, 2005).
To be the most effective, it is recommended to have a shallow basin (10-30 cm) far above the groundwater table. This allows for high infiltration rates and easy maintenance because of the high water turnover rate and quick drying (Bouwer & Rice, 1989). Common infiltration rates for recharge basins are 0.3-30 m/day. If the bottom of the basin is clear of sediment or other clogging materials and has a deep groundwater level below, the infiltration rates can be the same as the vertical hydraulic conductivity of the soil (Bouwer & Rice, 1984).

The benefits of the recharge basin method is that the basins are feasible and have low maintenance (Todd & Mays, 2005). Drawbacks of the basins are that they need deep groundwater table levels and they sometimes clog. For basins that control clogging with pretreatment, the water table must be at least 0.5 m below the bottom of the basin. For systems that have a clogging layer, the water table depth should be at least two times the width of the basin (Bouwer H., 1990). Soil clogging is caused by accumulation of suspended solids on the bottom and banks of the infiltration area. Suspended solids that can cause clogging are inorganic, such as soils and sediments or biological, such as algae or bacterial flocks. Having intermittent periods of drying in the basin will help reduce the growth of biological suspended solids. If there is not enough drying in the basin, biofilms can also grow on the bottom, lowering the infiltration rate of the basin. Clogging layers have a low permeability and, hence, they reduce infiltration rates (Bouwer H., 1982). Pre-sedimentation basins may be needed to reduce the amount of suspended solids in water before it goes into a recharge basin (National Research Council, 1994).

The recharge basin at the farm site surface elevation is just over 48 m above sea level. Piezometer data shows that the groundwater table near the recharge basin is fluctuates between 45 to 51 m throughout the year. When the recharge starts at the beginning of the wet season, the groundwater table is below the basin, and at the end of
the wet season the groundwater table is above the bottom of the recharge basin, causing ponding. The design parameters suggested by Bouwer are met for the farm site recharge basin for most of the time, allowing for high levels of infiltration. There is no pretreatment for the basin of interest, but clogging is not expected to be a large issue at this site. The basin in this study is seasonal, so biological clogging factors can be ignored. The biological constituents will dry out when there is no rain, not allowing for them to impact the basin. Also, inorganic suspended solids are not expected to be problematic because there is vegetation covering the surrounding areas, preventing mass transport of sediment. To completely ensure there is no clogging, scraping of the bottom of the basin is done typically biannually by the landowner.
CHAPTER 3: Data

The data described in this chapter is the initial data used to develop the GMS model. Some of these values were calibrated later to match water level observations.

3.1 Layers and Elevations

Three layers were used to represent the groundwater system. Layer 1 represents the topsoil and is considered to be an unconfined layer. Layer 2 is the confining layer or aquitard, and Layer 3 is the bottom, confined layer representing a potentially water-bearing alluvium. The ground surface elevation data came from a LIDAR survey of the Santa Rosa Creek Watershed done by PG&E (2013) (Figure 9). The ground surface elevations represent top elevation of layer 1. The top of layer 2 elevations (bottom elevations of layer 1) are the same as the layer 1 but has 5 m subtracted from it. This was done because borehole drillings showed that a clay layer starts about 5 m below the ground surface in the farm site area (Malama, Solum, & Nicholson, 2019). The bottom of layer 2 is the same as the top of layer 2 with an additional 5 m subtracted from it. This was also done to match the findings from Dr. Malama’s soil exploration report. This model in this report simplifies the elevation variation, but it is consistent with the data from the previous reports done.
Figure 9: Top of Layer 1 elevation raster clipped to the GMS model outline and converted to a topographical map.

The bottom elevation of the groundwater model, representing an impermeable media, was interpreted from the Tim Cleath Report by Dr. Muleta (Cleath, 2019) (Figure 10). Dr. Muleta processed the contour map Cleath made into a raster file for GMS. For this study, the bottom elevations did not cover the entire model, so assumptions were made on the northwestern side to extend the raster. This was done so there was enough data for GMS to make grids around the retention basin.
Figure 10: Bottom of Layer 3 elevation raster clipped to the GMS model outline and converted to a topographical map. The raster is shown as the background for better visualization.

### 3.2 Layer Hydraulic Properties

Hydraulic conductivities, horizontal and vertical anisotropies, specific yields, and specific storages for the three layers were provided by Dr. Muleta’s calibrated model (Muleta, 2020). The model defines horizontal anisotropy as “the ratio of hydraulic conductivity along columns (north-south for the site) to hydraulic conductivity along rows (east-west for the site)” and vertical anisotropy as “ratio of horizontal (along the rows) to vertical hydraulic conductivity” (Harbaugh, Banta, Hill, & McDonald, 200). The horizontal and vertical anisotropies for all layers was assumed to be 1. Layer 1 has the highest hydraulic conductivity, followed by layer 3 and then layer 2. Layer 2 should have the
lowest conductivity as it is a confining clay layer. Layer 1’s hydraulic conductivity was assumed homogenous for the site as shown in Figure 11.

Figure 11: Screenshot from GMS showing Layer 1’s hydraulic conductivity distribution. The light blue line represents the ephemeral waterway and the purple lies show head boundaries.

Hydraulic conductivity and other parameters for layer 2 were assumed based on the confining layer properties, which is composed of clay (Heath, 1983). For area next to the ephemeral channel that runs through the northern side of the model, layer 2 properties were assumed to be identical to those of the northern portion of layer 3 (Figure 12).
Figure 12: Layer 2 hydraulic conductivities. The light orange lines show areas surrounding the ephemeral channel with a higher conductivity.

Layer 3, the confined layer, properties were provided by Dr. Muleta and were obtained from the USGS report. The hydraulic conductivity is higher than layer 2 but lower than layer 1 (Figure 13). Layer 3’s hydraulic properties were split into two sections, a northern and a southern portion. The data given showed the hydraulic conductivity as constant throughout the both sections of layer.
Figure 13: Layer 3's hydraulic conductivity. The bright orange square in the southern side of the model represents the agricultural well.

### 3.3 Variable Head Boundary Conditions

Santa Rosa Creek as well as the boundaries on the southeast and the southwest boundaries of the model were represented as variable head boundaries. These boundaries were shown in purple in Figure 9. The boundaries were required because they represent physical boundaries where the site represented in this model was “cut-out” from the larger Santa Rosa Groundwater basin. In reality, Santa Rosa Creek interacts (i.e., feeds/receives flow) with the aquifer modeled in this study. Likewise, groundwater may flow into the modeled site along the northeastern boundary and flows out of the modeled site along the southwestern boundary. The variable head boundaries represent the interactions between the aquifer modeled here with the creek and with the other two boundaries. Daily heads at the creek were determined by adding daily depth of
flow values to the top elevations of layer 1 for segments along the creek (Figure 14). The stage (depth of water) values were estimated based on the time of the year. The maximum was assumed to be 1.5 m January through March and slowly declined down to 0.1 m in the dry season. The same stage values were used for every location along the creek boundary.

![Figure 14: Three Santa Rosa Creek boundary head values.](image)

Variable head values along the southeast and southwest boundaries were determined from the SRC Creek daily heads at the east and west locations, respectively. Heads at the SRC’s east and west edges were used as the southeast and southwest boundary head values, respectively. Then, a hydraulic gradient of 1% was assumed from north to south to determine head values along the northeast and northwest boundaries (Figure 15).
3.4 Creeks

A shapefile with the creeks in the Santa Rosa Creek Watershed was provided by Dr. Muleta (Muleta, 2020). This shapefile came from the SWAT model he created. In the model there are two creeks, an ephemeral channel that runs through the northern side of the model, and the Santa Rosa Creek (Figure 4).
The shapefile provided by Dr. Muleta included the widths and location of the streams. Additionally, Dr. Muleta provided the stream conductance as well as daily streamflow data from the SWAT model (Figure 16). The ephemeral channel on the northern side of the model has a low stream flow due to it being a rain-dependent stream that eventually connects into Santa Rosa Creek. The Santa Rosa Creek streamflow data was not used as a creek because the stage from the stream was calculated and incorporated into the boundary head values.
The sinuosity for the stream was calculated by using Equation 1,

\[
\text{Sinuosity} = \frac{\text{Length of Stream Channel}}{\text{Length of Straight Line Distance}}
\]  

(Equation 1).

ArcMap was used to find length of the stream channel and the straight line from the beginning to end.

3.5 Agricultural Well

Location of the irrigation well and estimates of pumping from the well were supplied by Dr. Muleta (Figures 17 and 18). The well pumps from the confined layer, and pumping rates were determined based on irrigation demands for the crops at the farm site. The irrigation demand estimates came from a consumptive water use analyses made using the CropWAT software. Emma Erickson, a graduate student in the Civil and Environmental Engineering Department at Cal Poly SLO, determined the irrigation demand for the Santa Rosa Creek Watershed as an independent study project for Dr. Muleta (Erickson, 2019). Dr. Muleta used the irrigation demands to determine monthly
pumping rates for the irrigation wells in the groundwater basin. Crop data including crop type and acreage were obtained from CropScape, USDA’s crop data site (USDA, 2020). CropWAT uses crop types and acreage, climate, and other parameters to estimate irrigation demands (Smith, 1992). The crops at the farm site are 6.60 ac of citrus and 7.47 ac of avocados according to CropScape. This was confirmed using Google Earth Pro. As expected, the irrigation requirements during the wet season are much lower than the dry season due to precipitation supplying the crops with most of the water they require.

Figure 17: Map of the agricultural well location in the model area.
3.6 Recharge Rates

Daily recharge rates for each subbasin inside the model as well as for the recharge basin were supplied by Dr. Muleta (Figure 19). The recharge rates for the subbasins generally were only a few millimeters a day, not allowing for much flow into the groundwater basin. The subbasin outlines came from Dr. Muleta’s SWAT model (Muleta, 2020) (Figure 20).
Figure 19: Daily recharge rates for the four subbasins in the model.

Figure 20: Map of the different subbasins within the model.
The recharge rates also came from the SWAT Model. Recharge rates at the farm site were estimated by Dr. Muleta based on the owner’s recollection of the filling and drying cycles of the basin and SWAT’s streamflow simulation for the ephemeral channel. Recharge rates for the basin are shown in Figure 21. The owner has a piezometric well that logs water levels in the basin that were used to calculate recharge. The basin’s location can be seen in Figure 4.

![Figure 21: Recharge basin daily recharge rates.](image)

### 3.7 Evapotranspiration Rates

Daily evapotranspiration rates were supplied from Dr. Muleta’s SWAT Model (Muleta, 2020) (Figure 22). The rates were assigned to the subbasins shown in Figure 20. The evapotranspiration surface layer was set to the ground elevation (top of layer 1), and the extinction depth of evaporation was assumed to be 2 m. Extinction depth represents depth (from the ground surface) beyond which soil evaporation cannot occur.
Figure 22: Daily evapotranspiration rates broken down by subbasin.

3.8 Observations for Calibration

There are three observation wells in the model area (Figure 23). These piezometric wells (i.e., KP1, KP2, and KP3) record water levels in the groundwater system. Data from these observation wells was collected by the property owner (Figure 24). This data was used to calibrate the groundwater model to better represent the groundwater system. There is also water level data for the irrigation well (i.e., K2) for the 1988-89 (Yates & Van Konyenburg, 1998). These water level values were assumed identical to 2016-17 for model calibration. Although these values are from decades ago, water level in the irrigation well is considered similar to water level in the Santa Rosa Creek. As such, no substantial inter-annual variability is expected in water levels at the irrigation well.
Figure 23: Map of observation wells included in the model.

Figure 24: Head data from the observation wells.
CHAPTER 4: Groundwater Model

4.1 Background

A groundwater model is a simplified representation of a real-world groundwater system. Although they are not wholly representative of every process in a groundwater system, models can be useful for decision-making. There are various methods used to model groundwater, including analytical and numerical methods (Kumar, 2019).

This study used GMS to create a numerical model to represent the groundwater system at the farm site. GMS, Groundwater Modeling System, is a graphical user interface (GUI) for various groundwater analysis programs including MODFLOW, SEAWAT, and others. This software was developed by Aquaveo, LLC in Provo, Utah (Aquaveo, LLC, 2019). MODFLOW is the modeling software used within GMS for this model. MODFLOW is a 3D, cell-centered, finite difference, saturated flow model developed by the USGS (McDonald & Harbaugh, 1988). MODFLOW can perform both steady state and transient analyses and has a wide variety of boundary conditions and input options. It accomplishes this using a numerical approach to modeling with different analysis packages.

Groundwater flow equations that represent the movement of groundwater through porous earth material are derived from the partial-differential equation (Harbaugh, 2005),

\[ \frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) + W = S_s \frac{\partial h}{\partial t}, \]  

(Equation 2)

where

- \( K_{xx}, K_{yy}, \) and \( K_{zz} \) are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T),
- \( h \) is the potentiometric head (L),
\( W \) is a volumetric flux per unit volume representing sources and/or sinks of water, with \( W > 0.0 \) for flow into the system \((T^{-1})\), \( S_s \) is the specific storage of the porous material \((L^{-1})\), and \( t \) is time \((T)\).

This equation describes groundwater flow under nonequilibrium conditions through a heterogeneous, anisotropic medium (Harbaugh, 2005). When Equation 2 is coupled with flow and/or head conditions at the boundaries of an aquifer system and specification of initial-head conditions, a mathematical representation of a groundwater flow system can be created.

An example of an analytical model is the Hantush Equation, which computes the size of groundwater mounds in response to percolation (Hantush, 1967). The assumptions in the Hantush Equation are that the infiltration basin causing the mounding is square or rectangular or circular, the aquifer is homogeneous and isotropic, flow is strictly horizontal, the change in aquifer saturated thickness relative to original saturated thickness is trivial, and the infiltration rate is constant (Carleton, 2010). These assumptions drastically limit the model, but it allows for a simpler and faster analysis. A downside to analytical solutions is that they only work for simple systems. To solve complex systems, such as the groundwater basin of interest in the study, a numerical method must be employed.

The numerical method that MODFLOW uses is known as the finite-difference method. The finite-difference method is based on the continuity equation, “all flows into and out of the cell must be equal to the rate of change in storage within the cell” (Harbaugh, 2005). The continuity representing flow in a cell is as follows (Harbaugh, 2005),
\[ \sum Q_i = SS \frac{\Delta h}{\Delta t} \Delta V, \]  \hspace{1cm} (Equation 3)

where

- \( Q_i \) is a flow rate into the cell (L\(^3\)T\(^{-1}\)),

- \( SS \) has been introduced as the notation for specific storage in the finite-difference formulation; its definition is equivalent to that of \( S_s \) in Equation 2 - that is, \( SS \) is the volume of water that can be injected per unit volume of aquifer material per unit change in head (L\(^{-1}\)),

- \( \Delta V \) is the volume of the cell (L\(^3\)), and

- \( \Delta h \) is the change in head over a time interval of length \( \Delta t \).

MODFLOW uses this equation in every user-specified sized cell at every stress period and time step to create a model. Stress periods are portions of the model simulation where the stresses (i.e., fluxes such as pumping rate, ET, recharge) are constant. Time step is a portion of each stress period where the head at each cell is calculated (Harbaugh, 2005).

The necessary components of most every numerical groundwater model are boundaries, recharge rates, hydraulic conductivities and storage, interaction, and leakance parameters (Brandt, Johnson, Elphinston, & Ratnayaka, 2017). Numerical model construction is usually an iterative process because parameters need to be refined. Initial inputs may not work well requiring further analysis. Even when it works, a model may not be complete or comprehensive enough. The model must be calibrated to the real-world groundwater basin with measured data. This measured data is most often water levels at different points throughout the basin of interest and/or streamflow at one or more sites. To calibrate, the input parameters are adjusted until the model “accurately” represents the groundwater basin (Brandt, Johnson, Elphinston, & Ratnayaka, 2017).
GMS is used in this study to create a numerical MODFLOW model using the conceptual model approach. Instead of defining every grid’s properties and data within the model manually, the conceptual model method of building a MODFLOW model allows a user to define the model properties from GIS layers. When the needed GIS data is available, the properties of the GIS data can be transferred to the appropriate grids. This allows for a quicker modeling process and quicker editing (Kumar, 2012).

4.2 Setup

Building the GMS model started with processing the geospatial data in ArcMap. Then the processed data was imported into GMS to create a model of the farm site groundwater basin.

4.2.1 ArcMap

Data from Dr. Muleta in raster and shapefile formats were clipped to the extents of the granular, 2 m resolution, model. The model extents were determined from geophysical boundaries as well as potential impact of the recharge basin. Data that was clipped included the surface elevation LIDAR survey data, the top elevation for layer 3, and the bottom of layer 3 elevation raster datasets, as well as the creeks, subbasins, and wells shapefiles. Additionally, all files must be in the same projection for GMS to function properly. The projection for this study was Albers Equal Area Conic Zone with a datum of NAD83 and units in meters.

Zones of hydraulic properties were created based on changes in geolocation such as near Santa Rosa Creek, south of Santa Rosa Creek Rd., the lower agricultural area, the upper agricultural area, and the northwestern hillslope (Figure 25). Also, as mentioned in Chapter 3.2, a zone around the northern ephemeral channel had to be created in layer two. This was because the thought is that there is not a confining layer underneath stream, allowing for better recharge.
Figure 25: Map of hydraulic property zones within the model.

Once, all the data was clipped, and the different zones were created. All the ArcMap processed data was imported to GMS to create a groundwater model of the farm site.

4.2.2 GMS

The model started by converting the model outline shapefile into a coverage in GMS. Coverages are mapped data for specific features that can be then mapped to the MODFLOW grid cells to add data to a model. Coverages are grouped under conceptual models (Aquaveo, LLC, 2019). The model outline coverage was set as the extents of the MODFLOW model, and the active cells used were created based off the outline shape. The MODFLOW grid was created with a 2 m wide cells in the x and y directions and 3 vertical layers going downwards. The elevation raster datasets were then mapped to the
cells (Figure 26). Estimations were made for the thickness of the layers for where there were overlaps using the GMS MODFLOW Model Check and Elevation Editor functions.

![Figure 26: 3D GMS MODFLOW model display with top of cell elevation values (m).](image)

After the MODFLOW grid and elevations were set, MODFLOW was set to a Transient model and the Newton (NWT) version with the Upstream Weighting (UPW) flow package. The UPW package allows for drying and rewetting of cells within a model, but the only way to use UPW is if the NWT version is selected. The NWT version uses a different solver than the default version and requires twice as much memory. The optional packages Time-Variant Specified Head (CHD), Stream (STR), Multi-Node Well (MNW1), Recharge (RCH), Evapotranspiration (EVT), and Parameter Estimation with Advanced Spatial Parameterization (PEST-ASP) were activated as well. For the initial model, there were 731 stress periods all with a time step of 1 day from 12:00 am January 1, 2016 to 12:00 January 1, 2018. Although data for all of 2015 through the end of 2019 was available, only 2016-2017 data was used to for the initial model and to calibrate to save computing time.
Each shapefile, raster, and transient flux dataset was brought into GMS, converted to a coverage, and then mapped to the MODFLOW model. The coverages created for the model mimic the data given in Chapter 3. These coverages were as follows; the extents of the model, hydraulic properties for layer 1, hydraulic properties for layer 2, hydraulic properties for layer 3, boundary head conditions, streams, wells, recharge rates, evapotranspiration rates, and observations (Figure 27).

![Figure 27: GMS interface with all the coverages mapped.](image)

The hydraulic properties for each layer were mapped to MODFLOW. Displays of these values can be seen in figures 9, 10, 11, and 12 in Chapter 3.2.

The variable head boundary condition values for the Santa Rosa Creek and for the boundaries on the southeast and southwest of the model were set to transient, and the head values were imported into the boundary coverage. Another boundary coverage was created for the Santa Rosa Creek boundary and had data uploaded to it as well. Then the boundary coverages were mapped to MODFLOW under the CHD package (Figure 28). The CHD package works by assigning a specific head value at each cell and stress period defined. These values are set and will not be altered when MODFLOW
is ran. Additionally, the starting heads for MODFLOW were set to the top elevation for layer 1 to ensure no errors occurred in the first stress period.

Figure 28: GMS model of starting heads in layer 3 (m). The boundary heads are shown in purple and the well is shown as an orange square.

The rain-dependent stream inputs were located in the stream coverage, which was then mapped to the STR package. The stream was broken down into smaller segments to assign more detailed elevations. Each stream segment had a beginning and ending elevation (m), conductance (m²/d/m), width (m), sinuosity, and roughness coefficient (n). The STR package calculates stage height using Manning’s Equation (Prudic, 1989),

\[ Q = \frac{K}{n} A R^{2/3} S^{1/2} \]  
(Equation 4)

where,

\( Q \) is the flowrate of an open channel (ft³/s or m³/s),

\( K \) is the flowrate of an open channel (ft³/s or m³/s),

\( A \) is the cross-sectional area of the stream (m²),

\( R \) is the hydraulic radius (m),

\( S \) is the streambed slope (degree),

\( n \) is the roughness coefficient.
\( K \) is a constant based off units (1.49 for English, 1 for metric), 
\( n \) is the Manning’s roughness value for the channel, 
\( A \) is the cross-sectional area of the channel (ft\(^2\) or m\(^2\)), 
\( R \) is the hydraulic radius of the channel (ft or m), and 
\( S \) is the longitudinal slope of the channel (ft/ft or m/m).

The flow, stream width and slope inputs for Manning’s Equation came from Dr. Muleta’s SWAT model. The Manning’s roughness value of 0.06 was used for this creek based off a USGS report for natural channels (Arcement Jr. & Schnider, 1989). The beginning of the stream had a transient incoming flow (m\(^3\)/d) assigned to it. These transient values can be seen in Figure 16 in Chapter 3.4. Once all the data was assigned to each stream segment, the coverage was mapped to MODFLOW under the STR package (Figure 29).

![Figure 29: Layer 1 top of cell elevations (m) with the streams shown in light blue.](image)
The well coverage consisted of only the agricultural well in the southern part of the model, see Figure 28. The screen elevations (m), well radius (m), and daily well flows (m³/s) were all inputted into the coverage. The well pumps only from layer 3, the confined layer, due to the elevations of the well screen. Once mapped to MODFLOW, the well was located under the MNW1 package. The MNW1 package is specifically designed to help with wells that span multiple layers in a model (Halford & Hanson, 2002). The well within this model is only located within layer 3, but this package was used because it is used in Dr. Muleta’s model.

Daily recharge rates were inputted for every subbasin as well as the recharge basin (m/d). To do this, the subbasin shapefile was converted to the recharge rates coverage, and then a polygon was drawn around the recharge basin (Figure 30). The recharge rates were opened into the polygons and then mapped to the MODFLOW model under the RCH package. The RCH package works by applying the recharge rate (m/day) to the top area of the cell (m²) to get a recharge volumetric inflow (m³/d) for each cell with a defined recharge (Aquaveo, LLC, 2019).
The daily evapotranspiration rates were loaded into the ET rates coverage for each subbasin. The subbasins were loaded into the coverage using the same process as the recharge rates, but without adding the extra polygon for the recharge basin. The coverage was mapped to MODFLOW under the EVT package. The EVT package calculates the volumetric evapotranspiration for each cell the same way the recharge rate is calculated, but with a extinction depth and surface (Banta, 2000). The extinction depth in this model was set to 2 m and the ET surface was set to the top of layer 1 as mentioned in Chapter 3.7.

The observation wells KP1, KP2, and KP3 were all inputted into the observation coverage as nodes with the real-world head values. This coverage was mapped to MODFLOW for calibration. The PEST-ASP package utilizes these observation points to calibrate the model.
Once all the coverages were mapped and all the data was entered into the
MODFLOW model, the 2016-2017 model was run. Head values from this model were
calculated at every time step, or in this case, day. The figure below is a visual example
of the head values (Figure 31).

![Head values](image)

**Figure 31:** Layer 3 head values (m) on 3/2/2017. The red areas show dry cell, which
means the head is below the top of the cell.

This initial run was not calibrated, so the model head values are not
representative of the real-world observations. The next step was to calibrate the model
to make the theoretical model match the observations.

4.2.3 Calibration

Once the 2016-2017 model was able to run to completion without errors, the
PEST-ASP package was used to calibrate the model. PEST was created by a third-party
to speed up the calibration process of models by back-calculating parameter values from
observations (Doherty, 2020). It is supported by many environmental modeling programs and is not just limited to use in MODFLOW. This package uses a variety of statistical formulas to obtain a more representative model.

There were nine estimated parameters for the model calibration. These parameters were hydraulic conductivities and horizontal anisotropies for layer 1, layer 2, layer 2 under the ephemeral channel as well as northern area of layer 3, and southern area of layer 3, in addition to the stream conductance for the ephemeral channel. The initial value for each parameter was set to the values in the coverages, but the minimum and maximum guesses were estimated. These parameters were chosen because there is no exact data for them. The values were estimated from soil types in the various studies done before. By calibrating the parameters, the hope is that parameters values would be more representative of the groundwater basin. PEST-ASP was set to run a maximum of 20 iterations to reduce error between the model simulated and the measured water levels at three piezometer wells and the irrigation well for January 2016-December 2017 period. The calibration took over 74 hours to finish (Figure 32).

Figure 32: Calibration interface for the 2016-2017 model after completion.
The calibrated parameters are given in Table 1. These parameters are valid, but there is concern with two of the hydraulic conductivities. First near the ephemeral channel in layer 2/northern areas of layer 3 reached the minimum estimated value of 0.1 m/d. Also, layer 3 near Santa Rosa Creek reached the maximum estimated value of 50 m/d. These values were accepted because they are reasonable maximum and minimums for the site.

Table 1: PEST Calibration Parameter Summary Table

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>HK_1001</td>
<td>Hydraulic Conductivity of Layer 1</td>
<td>12.6 m/d</td>
</tr>
<tr>
<td>HK_3001</td>
<td>Hydraulic Conductivity of Layer 2 near the ephemeral channel and Northern Layer 3</td>
<td>0.0106 m/d</td>
</tr>
<tr>
<td>HK_5001</td>
<td>Hydraulic Conductivity of Layer 2</td>
<td>0.100 m/d</td>
</tr>
<tr>
<td>HK_7001</td>
<td>Hydraulic Conductivity of Southern Layer 3</td>
<td>50.0 m/d</td>
</tr>
<tr>
<td>HANI_2001</td>
<td>Horizontal Anisotropy of Layer 1</td>
<td>1.00</td>
</tr>
<tr>
<td>HANI_4001</td>
<td>Horizontal Anisotropy of Layer 2 near the ephemeral channel and Northern Layer 3</td>
<td>1.00</td>
</tr>
<tr>
<td>HANI_6001</td>
<td>Horizontal Anisotropy of Layer 2</td>
<td>1.00</td>
</tr>
<tr>
<td>HANI_8001</td>
<td>Horizontal Anisotropy of Southern Layer 3</td>
<td>1.00</td>
</tr>
<tr>
<td>STR_9001</td>
<td>Stream Conductance of the Ephemeral channel</td>
<td>0.0296 m²/d</td>
</tr>
</tbody>
</table>

A comparison of the model simulated and measured water levels is given in Figures 33 and 34. Although the simulated values are not perfect match, they fairly represent the measured water levels. To further examine the calibrated model, a 4-year long, 2015-2019, model run was made using the calibrated parameters values.
Figure 33: Observed head (m) values (triangles) at KP1 compared to calibrated model head values (circle with lines) plotted over time.

Figure 34: Observed head (m) values (triangles) at K2 compared to calibrated model head values (circle with lines) over time.
4.2.4 Verification

A verification run was done for the 2015-2019 model. This run used the calibrated parameters for the 2016-2017 model and then was checked against the observed head values (Figures 35, 36, 37, and 38). Although there are still differences between the model and the observed values, these differences were acceptable based on the available data. It can be said that the model generally represents the groundwater basin at the farm site. The 2015 model values do not follow the trend of the observed data as well as the other years. This discrepancy in the 2015 outputs could be caused by 2015 being a relatively dry year in California.

Figure 35: KP1 model heads (m) compared to the observed heads for 2015-2019.
Figure 36: KP2 model heads (m) compared to the observed heads for 2015-2019.

Figure 37: KP3 model heads (m) compared to the observed heads for 2015-2019.
For a model to be truly representative and informative, an uncertainty analysis needs to be performed on the model outputs. This was not done because Cal Poly San Luis Obispo does not own the GMS license that enables performing uncertainty analyses. For the purposes of this report, model results generated using the calibrated model were considered satisfactory.
CHAPTER 5: Results & Discussion

The primary result from this report is a working, calibrated GMS model for the farm site. This model allows for hydrologic soil parameters to be analyzed and for the flow of water from different locations to be depicted.

5.1 Parameters

The calibrated parameters are shown in Table 1. The values of these parameters provide some insights on the characteristics of the aquifer. By knowing the calibrated hydraulic conductivities, inferences about the soil can be made.

Table 1 (for reference only): Identical to Figure 4 in Chapter 4.2.3

<table>
<thead>
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<td>Horizontal Anisotropy of Layer 2 near the ephemeral channel and Northern Layer 3</td>
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<td>Horizontal Anisotropy of Layer 2</td>
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<td>Horizontal Anisotropy of Southern Layer 3</td>
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</tr>
<tr>
<td>STR_9001</td>
<td>Stream Conductance of the Ephemeral channel</td>
<td>0.0296 m²/d</td>
</tr>
</tbody>
</table>

The hydraulic conductivities confirm there is a layer of soil with good infiltration above a clay confining aquifer. At the moment, the expectation is that the confined layer (layer 3) is a water-bearing alluvium with “high” hydraulic conductivity. However, the calibrated parameters seem to indicate otherwise. The low hydraulic conductivity for HK_3001 (0.0106 m/d), shows that the hydraulic conductivity in layer 2 under the ephemeral channel is not higher than the rest of the clay confining layer and that the
northern section of layer 3 is actually comprised of a clay or soil with similar
characteristics to clay (Figure 39). This means that potential for recharge is low in the
northern area of the farm site. The southern portion of layer 3, near Santa Rosa Creek,
has a hydraulic conductivity of 50 m/d, showing that the aquifer is productive and could
be feasible for possible recharge. Recharging close to the creek, however, runs the risk
of the recharge entering the creek relatively fast (i.e., before the low-flow season), and
may not benefit the landowner as well as the ecosystem health.

Figure 39: Hydraulic conductivities of the soil in layer 3.

Also, the calibrated horizontal anisotropies for the all hydraulic conductivity zones
is 1.00, which is also identical to the assumed vertical anisotropy. This shows that water
disperses equally in the x, y, and z directions depending on the hydraulic gradient (slope
of the water table or the potentiometric surface). This means that the anisotropies do not
hinder water from the recharge basin from flowing towards Santa Rosa Creek and the higher hydraulic conductivity area in the southern portion of layer 3.

From the calibration, the hydraulic conductivity of layer 2, shown as HK_5001, was found to be the most sensitive parameter (Figure 40). This means that changes in the layer 2 hydraulic conductivity would have a large impact on the water levels at the piezometers and irrigation well. The next most sensitive parameter was the stream conductance in the ephemeral channel, followed by the hydraulic conductivity near the ephemeral channel/northern areas of layer 3. This implies that future data collection/measurement efforts would be more effective (in terms of improving the model's capability to better represent the aquifer) if they focus on characterizing properties of the confining layer (layer 2). That could help reduce uncertainty in the model predictions.

![Sensitivity Plot](image.png)

Figure 40: Parameter sensitivity plot for the calibrated model.

### 5.2 Flow Duration and Approximate Travel Times

The water from the recharge basin flows from the recharge basin to the southern portion of the groundwater mode (Figure 41). This is because the water is not being
allowed to flow quickly downwards (vertically) due to the clay in layer 2. The water flows in during the wet season from precipitation but is spending a long time in the confining layer before reaching layer 3.

![Figure 41: Monthly head changes in layer 1 from 1/15/2018-6/15/2018.](image)

The layer 3 head levels do not change much throughout the wet season (Figure 42). The basin does not appear to be recharging layer 3. This is due to the confining layer above it, as well as the northern portion having a low hydraulic conductivity. The water from the recharge basin does not seem to reach layer 3.
Figure 42: Monthly head changes in layer 2 from 1/15/2018-6/15/2018.

A cross-sectional view of the model showing the recharge basin confirms these findings (Figures 43 and 44). The layer 3 head elevations have little change throughout the year, but layer 1 is changing depending on the time of year. This also shows that the layer 3 high hydraulic conductivity allows that layer to recover quickly from pumping. It can draw water from the southern extent of the model (Santa Rosa Creek).
Figure 43: Heads (m) displayed in a north-south cross-sectional view from 1/15/2018-6/15/2018. The cross-section cuts through the recharge basin.
Figure 44: Heads (m) displayed in a north-south cross-sectional view from 7/15/2018-12/15/2018. The cross-section cuts through the recharge basin.

A flow path analysis was performed on water from the recharge well using the MODPATH extension in GMS. MODPATH uses an operational MODFLOW model to
track water particles from an area of interest. In this analysis of the farm site, MODPATH analyses were performed for 2016 and 2017 (Figure 45). Due to the nature of MODPATH, it was only possible to run the analysis for about the first 150 days of each year. In the dates analyzed for both years, it shows that the water does not flow into the underlying confined aquifer.

![Figure 45: MODPATH flow analysis with the surface elevation contours shown (2016 on the left and 2017 on the right).](image)

In the 2016 MODPATH analysis, the recharge basin was modeled as an injection well, and in the 2017 analysis, particles were assigned to the water table surface. By performing both types of analyses, it confirmed the water does not reach the underlying aquifer in the period modeled. Although the water does not percolate into the underlying aquifer, it begins to move towards layer 3 at the end of the dates analyzed (Figure 46). This shows that there is potential for water to infiltrate into the confined zone near the creek.
Figure 46: Side view of models with MODPATH analysis flow lines (2016 on top and 2017 below). The calibrated hydraulic conductivities are shown in the cells (blue is 50 m/d and red is 0.01 m/d).

In summary, if this model is considered representative, water from the recharge basin is not flowing into the underlying groundwater system. The clay-confining layer is preventing the water from flowing downward quickly. The southern portion is able to draw water from the surrounding aquifer, but the northern section of layer 3 has a low hydraulic conductivity, like clay, not allowing for recharge in that area. If there is no water-bearing layer in the northern portion of layer 3, it will make recharge in the area difficult.
CHAPTER 6: Conclusion & Recommendations

6.1 Conclusion

If this model is representative, the recharge basin does not appear to be assisting in raising groundwater levels based off the flow path analysis. The confining layer as well as the low conductivity soil in the northern portion of layer 3 prevents water from percolating deeper. It can be concluded that, based on the data available, recharging the groundwater basin in the northern portion of the site will not be effective. There is potential for recharge in the southern portion of the site. Another application of this model in the future could be to evaluate other artificial groundwater recharge methods.

6.2 Future Recommendations

Although this analysis does not recommend artificial groundwater recharge in the northern portion of the farm site, further work could either strengthen or dispute this recommendation. Also, this additional work and research would assist in evaluating recharge in the southern areas at the site. Adjustments within the GMS model as well as the input parameters would assist in improving the reliability of the results from this analysis.

6.2.1 Modeling Recommendations

There are further adjustments that could be done to the model to help improve the model. The hydraulic zone in layer 2 beneath the ephemeral channel and the northern section of layer 3 could be separated. Also layer 2 hydraulic properties could be split into zones similar to the split in layer 3. There should be three zones, the area beneath the ephemeral channel, a northern area, and a southern area. This would allow to check if the clay confining layer extends to the creek and impacts flow. Changing these parameters will increase computational time. The calibration time for these models
would extend past the 74 hours needed for this analysis. This increased time requirement made it infeasible for this study to incorporate these adjustments.

Another recommendation for modeling is to calibrate the model using all five years of data but perform this using a monthly calibration. By doing a monthly calibration this would greatly reduce the computing time, but it would still be able to calibrate to the trends of the observation data. This would allow for different combinations of parameter calibration to be tested.

6.2.2 Data Collection Recommendations

Expanded data on the farm site would also allow for an improved model. An ASTM soil classification on the soil cores from Dr. Malama’s soil exploration would allow for a more accurate initial hydraulic conductivity estimation of the layer 1 and layer 2 soils. It would also allow the model to calibrate to a smaller range. By doing this, the uncertainty in the model could reduce greatly. Additionally, from these results and after recalibrating the model, the sensitivity plot produced could be used to see what parameters could be improved with laboratory testing. As stated in section 5.2, hydraulic conductivity of the clay-confining layer was the most sensitive parameter for this study (Figure 40). This suggests that, laboratory testing of the borehole samples collected by Dr. Malama could be beneficial to improve this model.

Another source of error is the unknown soil underneath the clay layer. Having more soil explorations going deeper in the groundwater system would be useful to improve the model, to dispute or confirm findings of this model regarding properties of layer 3 for the northern part of the site, as well as to examine recharge opportunities. Also, this soil exploration would allow for a more accurate bottom elevation. The current model uses an estimation from the USGS report on SRC and having data on where bedrock is located could greatly improve the model. However, this could be a demanding and potentially expensive effort.
Finally, water level readings at the irrigation well would improve the model. Data from 1988-1989 as the data for 2016-2017 at the irrigation. Having up-to-date data on the water levels will allow for the calibration to use correct data and not introduce more assumptions into the model.
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