A GROUNDWATER MODEL OF THE SAN LUIS OBISPO VALLEY BASIN
USING COMSOL MULTIPHYSICS

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ABSTRACT

A Groundwater Model of the San Luis Obispo Valley Basin Using COMSOL Multiphysics

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A groundwater model of a subsection of the San Luis Obispo Valley basin was produced using COMSOL Multiphysics 5.5 software. The goal of this project was to create a general model using forward modeling techniques which would serve as the foundation for a more refined, complete, and calibrated groundwater hydrology model. The San Luis Obispo and Edna Valley basins are characterized as high-priority by the California Sustainable Groundwater Management Act because of historic overdrafting of groundwater reserves during periods of drought in the early 1990’s. Natural resource managers must use tools such as computer models to help forecast trends and predict future fates of groundwater reserves. COMSOL Multiphysics is a finite element modeling software which is more sophisticated than comparable hydrologic modeling software such as MODFLOW. A finite element model has not been constructed for the San Luis Obispo or Edna Valley aquifers, and therefore this project set out to begin the process of building such a model. Subsequently, the model was built with an irregular boundary path, homogeneous subsurface physical parameters, irrigation supply well pumping effects, and initial and boundary conditions. The product of this project has set forth the foundation on which a more complete model can be built.
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Chapter 1

INTRODUCTION

California’s variable and often times dry climate has led to an era in which groundwater must be managed very closely and responsibly. Groundwater has only recently become a regulated resource in California under the California Sustainable Groundwater Management Act (SGMA), signed into law by California governor Jerry Brown in 2014. Under this new legislation, groundwater basins that are considered medium and high-priority are under pressure to develop groundwater management plans that aim toward sustainable groundwater use within 20 years. Groundwater hydrology is an inherently complicated science and therefore it is vital to gather extensive and accurate data of the parameters which govern the flow and storage of groundwater. Since the state of groundwater cannot be easily assessed, it is useful to utilize modern tools such as computer models to generate manipulable forecasts to determine the fate of an aquifer under defined conditions (Christian-Smith and Alvord, 2016).

1.1 Project Goal and Objectives

The broader, more long term goal that extends beyond the scope of this project is to generate a working groundwater hydrology model for the entire region defined in Figure 3.1. Due to the time constraints of this degree program, complications experienced during this year due to COVID-19, other serious social strains, and the remote nature of the Spring and Summer 2020 quarters, creating a contiguous and calibrated model for this area is outside of the scope of this project. The results of this project will help inform decision makers as to the volume of water that can be
potentially stored in the aquifer, the flux and direction of groundwater flows, and the quantity of water that can be sustainably withdrawn for municipal and agricultural use.

This model was built upon existing groundwater elevation data along with predetermined saturated hydraulic conductivity values and heterogeneous aquifer materials and compositions. Eventually this model will be extended to include the entire San Luis Obispo and Edna Valley basins, but due to the time constraints of this project the genesis of the model will focus on the northeastern section of the San Luis Obispo Valley basin. The information obtained by creating this model will provide a strong visualization tool for predicting the behavior of the San Luis Obispo Valley groundwater basin and will also be an integral element in the decision making processes for sustainable groundwater management agencies and the management of the local groundwater basin per the requirements of SGMA.

The goal of this project was to use the finite element modeling software COMSOL Multiphysics (COMSOL) to generate a working groundwater hydrology model for the aquifers underlying the California Polytechnic State University (Cal Poly) campus within the San Luis Obispo Valley. The San Luis Obispo Valley aquifer has been categorized as a high-priority basin under SGMA protocol, therefore management of this aquifer has become exceedingly important in order to reach and maintain sustainable groundwater practices. More rudimentary models already exist for this region in California (Bates et al., 2019; Wallace, 2016), but there are strong advantages of using COMSOL, such as its ability to mesh multiple physical elements into a single model (Li et al., 2009). To achieve these goals, a gray-scale point cloud elevation image of the San Luis Obispo Valley was obtained to import into COMSOL as a model geometry. The geometry was extruded to give it subsurface depth and subsurface parameters such as hydraulic conductivity, porosity, and permeability were defined.
A water supply well was added to simulate water usage within the aquifer. Finally, a storage model was defined within COMSOL and the simulation was run for a predetermined time frame and results were analyzed.
2.1 Introduction

Groundwater modeling is an important tool to utilize when describing the characteristics of an aquifer and forecasting future fates of groundwater storage and use. Parameters that are determined from field observations and empirical measurements such as groundwater storage, hydraulic conductivity, and porosity can be defined in a model environment to help describe hydraulic behavior. The addition of boundary conditions, initial conditions, sources, and sinks make a model integral in predicting the future condition of the aquifer. The use of groundwater modeling is especially important in the state of California which passed the Sustainable Groundwater Management Act in 2014. This legislation mandates aquifers that are characterized as medium and high-priority to develop sustainable groundwater management plans and agencies to achieve sustainable practices within a short time-frame. The use of advanced modeling software will help groundwater agencies make critical management decisions that will lead to sustainability. COMSOL is a finite element modeling software capable of simulating subsurface flow and integrating various physical parameters into the modeling environment. The software’s user-friendly interface coupled with advanced meshing capabilities and its ability to integrate boundary conditions across an irregular boundary makes it a desirable platform for hydraulic modeling.
2.2 A Basic Overview of Groundwater Modeling

Aquifer characteristics (i.e. storativity, transmissivity, specific yield, etc.) have historically been difficult to describe and model. This is largely due to the heterogeneity and anisotropic nature of aquifers and our limited ability to describe an aquifer’s true characteristics. Many spatial and temporal assumptions must be made when describing a basin and interpolation can often times produce inaccurate models. Therefore, it is vital to collect accurate data when modeling a groundwater system and model results should not be taken as definite, concrete conclusions. Model calibration should be considered a necessary step in the groundwater modeling process in order to eliminate some of the uncertainty in data interpolation (Carrera et al., 2005).

Groundwater modeling is becoming increasingly more important as groundwater becomes a threatened resource. Groundwater is a difficult resource to manage because subsurface conditions are not easily identified; typically we rely on point measurements from wells or well logs and modeling groundwater behavior. Models are especially important within the context of problem solving for SGMA requirements because groundwater managers must use a 20-year "planning horizon" to forecast how their decisions will affect their groundwater basins. However, models are limited to the quantity and accuracy of field data and often make assumptions to streamline complicated groundwater processes such as estimated, or mean hydraulic conductivity for a heterogeneous area. This, coupled with the lack of consensus in model calibration procedures has led to limitations of model effectiveness (Christian-Smith and Alvord, 2016).
2.2.1 Subsurface Hydraulic Parameters

It is important to understand the physical mechanisms of groundwater movement to better manage depleted aquifers. One of the most important parameters to consider when describing groundwater movement is saturated hydraulic conductivity ($K_{sat}$). Saturated hydraulic conductivity is a porous media’s ability to transmit water through its void space under saturated conditions (Sarki et al., 2014). Water moves through porous media as a response to changes in pressure-gradient, gravitational, absorptive, and osmotic forces (Klute, 1965). The main factor that determines $K_{sat}$ (Equation 2.1) is soil texture, or the percentage of sand, silt, and clay particles within the porous media (texture does not include organic matter). In general, a soil with higher percent sand will transmit water easier than a soil with higher percent clay because of larger and more interconnected void space (Dunn and Phillips, 1991).

Hydraulic gradient (Equation 2.1), or the change in groundwater elevation over a given length, is also very important to consider when creating a groundwater model. Groundwater elevation data is obtainable via water level sounders inserted into monitoring wells. Water level data can also be collected using a pressure transducer which is suspended in the casing of a monitoring well below the water table where it collects pressure data that can be transformed into groundwater elevation data. One of the benefits of using a pressure transducer is the temporally rich data from continuous collection over time. Groundwater elevations (groundwater head) are often input into modeling software to create boundary and initial conditions over the model geometry and are integral in the calibration process.

Hydraulic flow rate through soil has long been estimated using the Darcy’s Law flux equation:
\[
q = -K_x \frac{\partial h}{\partial x} i - K_y \frac{\partial h}{\partial y} j - K_z \frac{\partial h}{\partial z} k
\]  

(2.1)

In this three dimensional Darcy’s Law equation \( q \) is fluid flux through a porous media; \( K_x, K_y, \) and \( K_z \) are saturated hydraulic conductivities in the \( x, y, \) and \( z \) directions assuming anisotropy in a homogeneous aquifer; \( \frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}, \) and \( \frac{\partial h}{\partial z} \) are the hydraulic gradients in the \( x, y, \) and \( z \) directions. The following assumptions are made to maintain the validity of Darcy’s law: three dimensional, laminar flow, and anisotropic, homogeneous aquifer properties. Although many assumptions must be made to utilize Darcy’s law, it provides a basic and reliable physical relationship between porous media and the fluid that flows through it.

The parameters and equation discussed above are among the many that exist and can be utilized within a modeling environment. Others that may be used include, but are not limited to the following: storativity, transmissivity, specific yield, specific retention, porosity, and physical boundaries (streams, lakes, bedrock, faults, etc.). These parameters play a vital role in creating and, more importantly, calibrating the model.

2.2.2 Governing Groundwater Flow Equations

Along with the governing flow equations, the type of boundary condition used in modeling and calculations is important as well. There are three types of boundary conditions found in physical sciences and engineering, including hydrogeology: the Dirichlet condition (Equation 2.4), the Neumann condition (Equation 2.5), and the Robin condition. The Dirichlet boundary condition prescribes a hydraulic head at a boundary, the Neumann boundary condition prescribes a fluid flux at a boundary,
and the Robin boundary condition is a combination of the Dirichlet and Neumann conditions. The Dirichlet boundary condition is popularly utilized because of the accessibility of hydraulic head data that is made available through groundwater elevation measurements.

It is important to understand the governing equations which can mathematically describe the flow of groundwater and which are used in hydraulic modeling. The governing equation that describes the flow of groundwater in a heterogeneous confined aquifer and in three dimensions is as follows:

$$\frac{\partial}{\partial x} \left( K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial h}{\partial z} \right) = S_s \frac{\partial h}{\partial t} \pm Q_w \delta(x - x_i) \quad (2.2)$$

where $K_x$, $K_y$, and $K_z$ are hydraulic conductivity in the $x$, $y$, and $z$ directions $[L/T]$; $\mathbf{x}$ is vector notation for $x$, $y$, and $z$; $S_s$ is specific storage $[1/L]$; $\delta$ is the three dimensional Dirac delta function; and $Q_w$ is the source or sink function (+ for source, - for sink) $[L^3/T]$.

Equation 2.3 describes initial conditions in terms of hydraulic head:

$$h(x, y, z) = h_0(x, y, z) \quad x, y, z \in \Omega \quad (2.3)$$

where $h_0(x, y, z)$ is the initial hydraulic head $(L)$ and $\Omega$ is the flow region. Equations 2.4 and 2.5 describes boundary conditions for the confined aquifer example:

$$h(x, y, z) = h_1(x, y, z, t) \quad x, y, z \in \partial \Omega_1 \quad (2.4)$$
\[ K \frac{\partial h}{\partial n} = q_2(x, y, z, t) \quad x, y, z \in \partial \Omega_2 \]  

(2.5)

where \( t \) is time, \( \frac{\partial}{\partial n} \) is the normal derivative, \( \partial \Omega \) is the boundary region \( (\partial \Omega_1 \cup \partial \Omega_2 = \partial \Omega) \), \( h_1(x, y, z) \) is the known hydraulic head at the boundary \([L]\), and \( q_2(x, y, z) \) is the known flux at the boundary \([L^3]\) (Meenal and Eldho, 2011). Equation 2.4 is a Dirichlet boundary condition where \( h_1 \) is a known prescribed function of both time and space. Equation 2.5 is a Neumann boundary condition where \( q_2 \) is a known prescribed function of time.

### 2.3 COMSOL Multiphysics

#### 2.3.1 Model Geometry

COMSOL Multiphysics 5.5 is a finite element modeling software capable of solving a complex series of partial differential equations and handling coupled equations. This software can be used to solve a multitude of physical problems including, but not limited to, subsurface fluid flow and contaminant fate/transport (Li et al., 2009). Creating an accurate three dimensional geometry from which to build a groundwater model on presents certain challenges. COMSOL eases the challenges of constructing a model geometry with the ability to interpolate surfaces from an image. A gray-scale image of a geographical region can be imported into the program and COMSOL will interpret the landscape’s elevation. In this case, no effort beyond uploading an image file into the software is necessary to begin the process of creating a bespoke model geometry. Elevation data can also be uploaded in digital elevation model (DEM) or text file formats.
2.3.2 Porous Media Flow Module

The advantages of using COMSOL reach far beyond its ability to interpolate geometries from images. The software is relatively user-friendly compared to comparable products such as MODFLOW, an open source command line based software made available by the USGS (Chui and Freyberg, 2007). The user interface in COMSOL is easy to navigate and consists of logically positioned drop down menus and tabs. The Porous Media Flow module within COMSOL allows the user to choose between steady-state and time-dependent modeling, fully saturated or partially saturated flow, and uses parameters such as hydraulic head to set boundary and initial conditions. COMSOL employs Darcy’s Law and the groundwater flow equation when dealing with fully saturated, low velocity flow, and has the capability of applying Richard’s equation when dealing with partially saturated media. The software also implements the van Genuchten and Brooks and Corey empirical models to account for the retention of water within the subsurface matrix pore space when dealing with partially saturated problems (COMSOL, 2020). The coupling of strong mathematical processing along with a user-friendly interface makes this software a highly desired and sought after tool.

2.3.3 COMSOL Multiphysics and Groundwater Modeling

COMSOL has the ability to couple multiple complex hydrologic processes into a single model. In the past, integrating boundary conditions such as recharge due to precipitation and evapotranspiration into a groundwater model was difficult and often loosely coupled. COMSOL makes the integration of such important boundary conditions possible, resulting in a more accurate model which better simulates in-situ processes (Chui and Freyberg, 2007).
The COMSOL software package is also capable of modeling heat transfer in groundwater. A case study was performed on a metro tunnel construction project in China which implemented artificial ground freezing practices to stabilize and strengthen the soil. A model was used in order to determine the extent and direction of freezing relative to the cooling rods. Temperature gradients were generated from the freezing rod elements along with permeability distribution charts and Darcy flow lines (Hu et al., 2018). This study exemplifies the coupling of multiple physical processes within a single model and COMSOL’s large computing capacity.

2.4 Sustainable Groundwater Management Act

Natural resources, such as groundwater, have historically been considered fixed and indestructible under economic growth theories, but nature is constantly undergoing change and has the potential to be degraded (Dasgupta and Ehrlich, 2013). Groundwater, therefore, has become an externality to the growth of economies which has led to an unsustainable rate of consumption and an increasingly evident loss of groundwater reserves and storage, especially in semi-arid regions such as California (Figure 2.1). Groundwater contributes up to 60 percent of California’s water supply during dry years, and over pumping during seasons of drought has led to adverse impacts such as land subsidence, sea water intrusion in coastal regions, and domestic production wells being pumped dry (Christian-Smith and Alvord, 2016).
California governor Jerry Brown responded to this issue by passing the California Sustainable Groundwater Management Act (SGMA) in 2014 with the objective of delegating groundwater management decision making to local agencies with the oversight of state governance and regulations (Kiparsky et al., 2017). SGMA is the first piece of legislation to acknowledge that surface and groundwater systems are interconnected and that the management of groundwater is vital not only to maintain groundwater reserves but also surface water flows (Cantor et al., 2018). SGMA requires groundwater sustainability agencies (GSA) to manage basins to primarily avoid six undesirable results: depletion of groundwater supply, reduction of groundwater storage, seawater intrusion, degraded water quality, land subsidence, and impacts on surface water systems due to groundwater depletion (Kiparsky et al., 2017).

The lack of groundwater data in the state of California obstructed the progress of sustainably managing groundwater resources. In response to the lack of data, the California Statewide Groundwater Elevation Monitoring (CASGEM) program was created in 2009 to initiate state-wide groundwater elevation data collection and to compile and make the collected data available to the public (Perrone and Rohde, 2016). Basins were then characterized as low, medium, or high-priority based on a
series of criteria: the current population overlying the basin, the projected growth of the population over the basin, the quantity of water supply wells within the basin, the total quantity of wells drawing water from the aquifers within the basin, the quantity of irrigated land within the basin region, the degree to which the population relies on groundwater for municipal and industrial use, and how many known groundwater impacts exist and have been acknowledged (Marquez et al., 2017). Medium and high priority basins have been prioritized for the development of sustainable groundwater management plans.

It has proven difficult to establish the criteria for forming GSAs in the abridged time frame set by SGMA. SGMA has given local agencies the liberty to design appropriate governance to reach sustainability, but this leeway has come with a lack of concrete direction. Instead, SGMA has provided GSAs with a diverse list of regulatory and non-regulatory actions to choose from to customize their own plans (Kiparsky et al., 2016). Kiparsky et al. suggest that GSAs take into account nine criteria to use as tools when building their sustainability plans: scale, human capacity, funding, authority, independence, participation, representation, accountability, and transparency.

One of the preliminary steps to take in developing a sustainable groundwater management plan is to create a water budget for the basin in question. The water budget is a means to evaluate the flux of water in and out of a control volume. The act of analyzing the components of the water budget allows experts to evaluate the overall storage in a system and determine the degree of its sustainability in the long run (Marquez et al., 2017). The groundwater budget enables GSAs to plan and limit water use where possible to try and achieve sustainability within a desired or predetermined time frame.

Groundwater modeling will play an important role in forecasting the future status of medium and high-priority basins in California. Since GSAs are tasked with creating
plans that must achieve sustainability within a 20-year horizon, it is vital for them to be equipped with tools that can accurately predict the behavior of a certain basin under various changes in management. GSAs will have the ability to manipulate a model and input thresholds to aid in decision making. For example, a threshold could be set according to historical data to compute the amount of pumping that should be allowable within a basin and whether current pumping rates will result in overdraft and ultimately unsustainable yield. SGMA is the first groundwater legislation that acknowledges the fact that surface water and groundwater are connected, and accordingly has determined that GSAs must set forth regulations to avoid the depletion of surface waters that are connected to groundwater aquifers. In this case, coupled groundwater-surface water modeling capabilities must also be utilized by personnel within GSAs (Cantor et al., 2018).
Chapter 3

MATERIALS & METHODS

3.1 Background

The San Luis Obispo and Edna Valley basins located in the Central Coast of California are the primary study areas of this project (Figure 3.1). The valley is bound on the east by the Santa Lucia Range, on the west by the San Luis Range, overlies an area of about 12,700 acres, and is part of the Central Coast Watershed (San Luis Obispo County, 2020).

The goal of this project was to create a model for the area in and around the Cal Poly campus. Dr. Bwalya Malama, a research professor affiliated with the Natural Resources and Environmental Science department of Cal Poly, has conducted extensive groundwater hydrology and geophysics research within, and adjacent to, the bounds of the campus, making this area the ideal starting point for the model. He has dedicated multiple years of his research to drilling monitoring wells around the campus property, installing pressure transducers within them, and fabricating custom solar powered data collection stations to gather continuous groundwater elevation data. He and his research assistants have used a geotechnical push probe to extract soil cores for evaluation and analysis of aquifer physical properties such as porosity, hydraulic conductivity, and soil moisture characteristics. Further more, Dr. Malama has conducted pneumatic slug tests in various monitoring wells located on campus to classify the in-situ hydraulic conductivity of the aquifer media (Aurelius et al., 2017).
This region of California is characterized as having a temperate, mild climate. San Luis Obispo has an average high temperature ranging from 64°F in winter months to 80°F in summer months and an average low temperature of 41°F to 55°F in the winter and summer months, respectively. The study area receives an average of 20 inches of precipitation annually. The geology of the San Luis Obispo region is defined by impermeable rock of the Franciscan Complex with fill consisting of unconsolidated Miocene age, or younger, sediment that is thin, discontinuous, and complexly layered (Yates and Wiese, 1988).

The city of about 45,000 relies on surface reservoirs and groundwater for municipal water supplies. A drought period from 1987-1992 led to mandatory water rationing.
in 1989 and an increase in groundwater pumping in the early 90’s which resulted in land subsidence near water supply wells. The land subsidence was experienced by residence and business owners around the Bear Valley Shopping Center located on Los Osos Valley Road (Luhdorff et al., 2014). The continued overdraft of groundwater and drought conditions led the San Luis Obispo Valley basin to be classified as high-priority under the new SGMA criteria. Two groundwater sustainability agencies were formed in San Luis Obispo as a response to SGMA requirements: the County of San Luis Obispo Groundwater Sustainability Agency and the City of San Luis Obispo Groundwater Sustainability Agency. These agencies must collaborate to develop a groundwater sustainability plan by 2022 to be implemented in the next 20 years to reach sustainability goals (San Luis Obispo County, 2020).

3.1.1 Geologic Setting

The project area is located within the Southern Coast Range Province of California which is located north of the Transverse Range Province, west of the Great Valley Province, and south of the Klamath Mountains Province. The area is characterized by a subduction zone complex known as the Franciscan Assemblage, a forearc basin sediments, and a magmatic arc consisting of plutonic and metamorphic rocks of the Salinian Block (age range from Mid to Late Mesozoic to Holocene). The San Luis Obispo Valley region consists of sedimentary and aged meta-volcanic alluvial deposits derived from the Franciscan Formation. These deposits consist of unconsolidated to consolidated conglomerate, gravel, sand, silt, and clay. The underlying fill is very complex and mixed due to the San Andres Fault system’s activity. The active Los Osos fault, located on the western edge of the San Luis Obispo Valley, is outside of the bounds of this project. Highly weathered and fractured Serpentinite outcroppings
are present due to the unique proximity to the aforementioned subduction zone (San Luis Obispo City, 2013).

3.1.2 Hydrogeology

The San Luis Obispo and Edna Valley groundwater basins are separated by a rise in bedrock south of the San Luis Obispo Airport creating two separate drainage formations. The northwestern section of the Valley (i.e. the study area) is fed by San Luis Obispo, Stenner, and Prefumo Creeks and the southern end of the Valley is fed by tributaries of Pismo and Davenport Creeks. The entire basin encompasses an area of approximately 12,700 acres and lies within the Central Coast Watershed. The Edna Valley sub-basin includes an area of 4,700 acres and the San Luis Obispo Valley sub-basin area encompasses 8,000 acres. Groundwater is relatively shallow and resides predominantly in an unconfined aquifer. The basin is mainly recharged by precipitation, irrigation runoff, and streamflow. Groundwater contributed two percent of the annual water demands of the city of San Luis Obispo in 2011, though in dryer years the city becomes more reliant on groundwater for its municipal supply (San Luis Obispo City, 2016).

Within the project area (the Cal Poly campus and its immediate surroundings), groundwater levels vary from approximately 9 to 30 feet below ground surface (bgs). The water bearing formation in this area is characterized by soils consisting of fine to medium grained clayey sand, sandy clay, lean clay, and sandstone bedrock formation. The soils are characterized as loose to medium-dense and in some areas contain loose and scattered small gravel. The sandstone formation is generally encountered at depths ranging from approximately 10 to 20 feet bgs. Although the greater San Luis Obispo Valley aquifer is unconfined, there are indications that areas within the basin contain confining layers such as the sandstone encountered on the Cal Poly campus.
(California State GeoTracker, 2020). Average groundwater levels for the San Luis Obispo region for the years 2011-2019 are presented below in Figure 3.2.

![Figure 3.2: Average depth to groundwater for the San Luis Obispo Valley basin showing a steady decline in water levels through an eight year period (San Luis Obispo County, 2020).](image)

3.2 Model Geometry

A groundwater model was constructed using COMSOL Multiphysics 5.5. The software was installed on a Cal Poly laptop with a Windows 10 operating system. The model geometry was generated using COMSOL’s ability to interpolate geographical elevation data from point cloud imagery. The grey scale point cloud image of the San Luis Obispo and Edna Valley basins was produced from a TIF file obtained from the USGS National Map viewer (USGS, 2020). The base map was then uploaded
into Google Earth Pro where it was converted to a PNG image. The dimensions of the image were determined using the ruler tool in Google Earth and the latitude and longitude of the bottom left hand corner of the image was recorded as a reference point in order to scale the model geometry (Figure 3.3).

![Image of the interpreted elevation data after the gray-scale image of the San Luis Obispo Valley region was uploaded into COMSOL.](image)

**Figure 3.3:** Image of the interpreted elevation data after the gray-scale image of the San Luis Obispo Valley region was uploaded into COMSOL.

The image was uploaded into COMSOL using the user-friendly interface, the dimensions were specified from the measurements taken from Google Earth, and the basic geometry of the land surface was interpolated and produced using the *Parametric Surface* feature. An identical parametric surface was built directly below the first to scale the geometry to represent bedrock (Figure 3.4). After the second parametric surface was made, the top surface was deleted.
Figure 3.4: The stacked parametric surfaces with the bottom surface representing the scaled bedrock to be used as the starting point for the model geometry.

A work plane was created 700 meters above the parametric surface and made transparent allowing the parametric surface to be visible from the x-y plane view. The boundary of the domain was drawn manually to roughly follow the 400 foot elevation contour of the basin surrounding the Cal Poly campus using the Sketch function within the work plane interface (Figure 3.5). The curve was then converted to a solid and extruded downward 800 meters to intersect the parametric surface. This step gave the geometry subsurface depth which represents the aquifer volume. The solid and parametric surface were joined into a single solid which cropped away everything outside of the sketched boundary. The top section of the remaining domain (the air) was deleted. An Irregular boundary is a unique and powerful advantage of COMSOL.
Figure 3.5: A top-down view of the sketched boundary in blue on the work plane constructed above the parametric surface with the y-axis arrow representing north.

COMSOL is a finite element modeling software with the unique advantage of an advanced Mesh function which divides the geometry into small triangular subsections that fit the curves of the topography much better than other comparable software such as MODFLOW which uses rudimentary rectangular boxes. The fineness of the mesh can be customized within the user interface and is quick and user-friendly to manipulate. The mesh was set to the Extremely fine option in order to generate the most spatially accurate model possible.
3.3 Model Materials and Subsurface Parameters

3.3.1 Fluid Material

The material of the subsurface was specified as water and the default values for density, dynamic viscosity, and compressability were used (Table 3.1). Water is one of the built-in materials in COMSOL and was easily found in the materials library under the liquids tab. The entire model domain was selected to be assigned the water material properties.

Table 3.1: The properties of water used in the San Luis Obispo Valley aquifer model.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>998 ( [Kg/m^3] )</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>( 1.003 \times 10^{-3} [Pa.s] )</td>
</tr>
<tr>
<td>Compressibility</td>
<td>( 4.0 \times 10^{-10} [1/Pa] )</td>
</tr>
</tbody>
</table>

3.3.2 Storage Model

A storage model was added to define more specific aquifer properties. Water and its default properties was assigned as the fluid flowing through the domain, and domain material was assigned under the matrix properties. Within the matrix properties tab in the storage model, the permeability model parameter was specified to be hydraulic conductivity. The permeability model can be customized to be isotropic or anisotropic depending on the level of complexity desired. For the purposes of this model the diagonal (anisotropic) selection was made. The default linearized storage equation was utilized for this model and the compressibility of the liquid and matrix were manually defined (Table 3.2).
Table 3.2: Subsurface parameters used in the San Luis Obispo Valley aquifer model. These parameters were estimated based on current knowledge of the San Luis Obispo Valley basin. Refinement of these values should be considered during future model calibration.

<table>
<thead>
<tr>
<th>Subsurface Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.35</td>
</tr>
<tr>
<td>$K_x$</td>
<td>$2.94 \times 10^{-4} [m/s]$</td>
</tr>
<tr>
<td>$K_y$</td>
<td>$2.94 \times 10^{-4} [m/s]$</td>
</tr>
<tr>
<td>$K_z$</td>
<td>$1.00 \times 10^{-4} [m/s]$</td>
</tr>
<tr>
<td>Matrix Compressibility</td>
<td>$9 \times 10^{-9}[1/Pa]$</td>
</tr>
</tbody>
</table>

3.4 Initial and Boundary Conditions

3.4.1 Initial Conditions

An initial hydraulic head condition was applied to the entire geometry by defining the hydraulic head as $z$ across the parametric surface. Groundwater potentiometric surfaces generally follow the topography of the overlying ground surface and therefore, the initial hydraulic head condition was set to mimic the parametric surface elevation across the geometry. Future refinement of the initial hydraulic head condition should include calibration by means of inputting measured groundwater elevations from monitoring wells within the modeling study area. The generalization of the initial condition was executed for this iteration of the model because of time restraints.

3.4.2 Boundary Conditions

There were two boundaries on which the Dirichlet boundary condition were applied (Figures 3.6 and 3.7). The surface of the boundary was selected manually and the hydraulic head (Dirichlet) boundary condition was selected. An exponential decay
function was used to simulate the drop in hydraulic head across the boundary over time:

\[ h = ze^{-t/\tau} \]  

(3.1)

where \( \tau \) is the time constant of groundwater recession when storage in the higher elevations is depleted (Table 3.3), \( h \) is the hydraulic head applied to the boundary, \( z \) is elevation of the parametric surface in meters, and \( t \) is time in seconds.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_1 )</td>
<td>0.035</td>
</tr>
<tr>
<td>( \tau_2 )</td>
<td>0.085</td>
</tr>
</tbody>
</table>

Table 3.3: The values of the time constants used on the model generated boundaries (Figures 3.6 and 3.7).

Figure 3.6: The first domain section seen in blue with Dirichlet boundary condition (Equation 3.1) and \( \tau_1 \) time constant applied.
3.5 Integrating Supply Well Pumping Effects

The addition of water supply wells gives the user the ability to simulate withdrawal of water from the aquifer and therefore determine sustainable pumping rates. The addition of wells into the model geometry is a relatively simple process in the newest version of COMSOL (5.5). To construct a well, a line segment is built within the domain using two point coordinates and the Form Union feature to join the line to the geometry. The well is then assigned to the line segment using the Edges feature and the well characteristics such as depth, diameter, and mass flow rate are defined. The depth interval of the line segment was specified to coincide with the screened interval of the well because this is where the water is being withdrawn from the
aquifer. Screened interval along with well location, casing diameter, and estimated yield were determined from well completion reports. Water supply wells within the study area were located using the GAMA Groundwater Information System maps.

3.6 Time Dependent Study

COMSOL allows the user to choose from a stationary or time dependent study when building the model. For this project the time dependent option was chosen for the purposes of simulating future conditions of the basin. Before running the model, the time interval and overall simulation time is defined. After the simulation is done running the user has the ability to observe the model at each time interval. The time unit for this model was set to hours, the interval was set to 0.01 hours, and the total simulation time was set to 48 hours.
4.1 Final Model and its Components

4.1.1 Irregular Geometry Boundary

The boundary for the model geometry was constructed using the Sketch function within a work plane (Figure 4.1). This function enabled the delineation of a unique and specific boundary path within the modeling domain. The irregular boundary captured the entire groundwater basin within the study area (Figure 4.2). The ability to delineate an irregular boundary and capture more of the desired modeling area is one of the main advantages of using COMSOL. The San Luis Obispo Valley basin is broken up by geologic features such as Cerro San Luis Obispo and Bishops Peak, and using alternative modeling software such as MODFLOW would have inhibited the extent of the model geometry coverage. The intuitive modeling interface makes performing tasks such as creating an irregular boundary seamless.

The depth of the subsurface aquifer varies, with a thicker region toward the northern end of the geometry and a thinner section toward the south. The sketched boundary was extruded downward at a uniform distance from the work plane but the parametric surface is not flat, which resulted in varying aquifer thicknesses.
Figure 4.1: The sketched boundary in blue on the work plane constructed above the parametric surface with the y-axis arrow representing north.

Figure 4.2: The ground surface and underlying aquifer of the Cal Poly study area with surrounding hillslopes and valleys after the boundary depicted in Figure 4.1 was converted to solid and extruded (y-axis arrow is north).
The advanced meshing feature in COMSOL constructed a mesh which fit the undulating topography of the model geometry. The mesh was set to *Extra Fine* to create a more spatially accurate modeling domain (Figure 4.3). If a finer mesh is chosen for the simulation the computation time will increase, especially with a more complex model. When meshing flatter areas in the geometry where changes in groundwater elevation do not vary significantly, COMSOL generated larger triangular sections. In the more complex areas COMSOL refined the mesh to capture the rapidly changing topography more accurately.

**Figure 4.3:** The *Mesh* function in COMSOL breaks the model geometry into smaller triangular subsections to better define the undulating topography.

### 4.1.2 Subsurface Hydraulic Parameters

In order to simulate the effects of saturated hydraulic conductivity values in the model, the geometry was assigned a unique storage model. The storage model feature in COMSOL enables the customization of subsurface parameters such as the
fluid, storage, and physical properties. Due to time restraints experienced during the process of this project, a homogeneous, anisotropic storage model was utilized. In-situ hydraulic conductivity values vary greatly through an aquifer, and therefore this model and its storage model should only be considered a starting point for a more refined model domain.

After the storage model was added to the model domain, the simulation time was defined and the study was executed. Figures 4.4, 4.6, 4.8, 4.10, and 4.12 were generated which depicts the groundwater elevation and surface contours throughout a two day study. Darcy velocity flow line graphics were also generated for each of the time stamps (Figures 4.5, 4.7, 4.9, 4.11, and 4.13).

![Figure 4.4: The final model geometry of the San Luis Obispo Valley basin at the beginning \((t = 0)\) of the 2 day study. North is indicated by the \(y\)-axis arrow.](image)

Figure 4.4: The final model geometry of the San Luis Obispo Valley basin at the beginning \((t = 0)\) of the 2 day study. North is indicated by the \(y\)-axis arrow.
Figure 4.5: Darcy flow lines at the $t = 0$ time stamp.

Figure 4.6: The final model geometry of the San Luis Obispo Valley basin at the 6 minute time stamp during the 2 day study. Groundwater elevations dropped as the study began.
Figure 4.7: Darcy flow lines at the 6 minute time stamp. The water begins to flow from the higher elevation regions within the domain.

Figure 4.8: The final model geometry of the San Luis Obispo Valley basin at the 30 minute time stamp during the 2 day study. Groundwater moves down gradient toward the south.
Figure 4.9: Darcy flow lines at the 30 minute time stamp. The lines indicate the groundwater is now traveling laterally and further down gradient. Higher velocities are observed at steeper regions of the ground surface and at higher elevations (high hydraulic head).

Figure 4.10: The final model geometry of the San Luis Obispo Valley basin at the 1 day time stamp during the 2 day study.
Figure 4.11: Darcy flow lines at the 1 day time stamp. The flow lines converge in a path from regions of high hydraulic head to low hydraulic head at relatively slower velocities.

Figure 4.12: The final model geometry of the San Luis Obispo Valley basin at the end ($t = 48$hrs) of the 2 day study. Pressure contours have spread and the pressure across the domain has decreased, including the boundaries.
The general direction and magnitude of the Darcy flow lines indicate that the water is traveling fastest when descending steep slopes, then slows in the flatter regions of the domain and travels according to the local topography. The direction of the flow lines generally follow a path from high to low hydraulic head and mimic the direction of groundwater flow seen in San Luis Obispo. Physical boundaries such as San Luis Obispo Creek and Stenner Creek should be added to the geometry in order to more accurately define the Darcy velocity flow lines. There are discrepancies along the border of the geometry as seen by the flow lines curving under themselves. This could be due to the irregularity in elevation along the border path. Overall, the Darcy flow lines represent an accurate depiction of the magnitude and direction of groundwater within the model domain.

4.1.3 Water Supply Wells

A single water supply well was added to the model geometry. Many monitoring wells and domestic supply well data were available within the bounds of the model
geometry, but only one water supply well was located within the study area using the GAMA Groundwater Information System map. The well resides on the Cal Poly campus and is used to irrigate crops in field 25 which is adjacent to Santa Rosa St. A State of California well completion report was available and utilized to specify the well location, casing diameter, screen interval, and estimated yield. The well is located about 650 meters north of the Highland Dr entrance to the campus and is situated between various crop fields. The well is one foot in diameter, has a screen interval from 21 to 80 feet bgs, and has an estimated yield of 300 gallons per minute (19 Kg/s). The line segment was built according to the screened interval dimensions and joined to the model geometry. A well was then assigned to the line segment using the Edges function and the specific well parameters were defined.

The effects of pumping from the single irrigation supply well were not evident during the two day simulation. This is due to the relatively low pumping rate and the large domain from which it is drawing water from. The pumping rate, therefore, was increased to 100 Kg/s in an attempt to simulate multiple wells drawing from the domain. This still did not yield any visible results. It is assumed that if more supply wells were integrated throughout the model geometry that there would be a noticeable change in the resulting pressure.
Chapter 5

DISCUSSION

5.1 Gaps in Research

This model was intended to present a more detailed and accurate simulation of the San Luis Obispo Valley groundwater basin, specifically local to the Cal Poly campus and its surrounding basin. Finite element modeling software such as COMSOL Multiphysics have not been utilized to model this area in the past, leaving room for an improved groundwater model to be created.

5.2 Purpose of the Model

A model was created using COMSOL which contained irregular boundaries, a more advanced geometry mesh, homogeneous subsurface physical parameters, and the integration of supply well pumping effects. This project focused on the construction of the model geometry and assigning aquifer characteristics to the domain to simulate the San Luis Obispo Valley basin. This is what is called forward modeling, where the main purpose of the model is to simulate certain future outcomes such as groundwater elevation and effects of supply well pumping through time. The geometry was created successfully and captured the entire desired modeling area by utilizing an irregular boundary. The advanced mesh function was applied to the geometry and subsurface parameters such as saturated hydraulic conductivity were applied. Finally, supply wells were added to the geometry with specific well characteristics to simulate groundwater pumping effects.
5.3 Further Research

This model has not been calibrated using inverse modeling methods, which should be the next step in the process to a complete model. Evaluating the model outputs against field and empirical measurements should be conducted in order to calibrate the model. Once the model is sufficiently calibrated it will be more capable in forecasting future basin conditions and thus be a more useful tool for groundwater managers.

Furthermore, measured in-situ saturated hydraulic conductivity values should be applied within the domain in order to more accurately describe the behavior of the basin’s groundwater flow. A Diagonal saturated hydraulic conductivity model was used for this model domain which resulted in an anisotropic, homogeneous model. In this case, the hydraulic conductivity in the $x$, $y$, and $z$ directions were defined but applied across the entire geometry. In order to best simulate the heterogeneity of in-situ conditions, measured $K_{sat}$ values should be applied.

The model geometry should be extended to include the entire San Luis Obispo Valley basin and Edna Valley basin. The addition of all water supply wells, both irrigation and municipal water supply, within the basin is necessary to generate an accurate water budget and determine sustainable pumping rates. The addition of boundary features such as lakes, streams, and faults should also be added to the model geometry to better define groundwater behavior.
Chapter 6

CONCLUSIONS

A model was constructed encompassing a subsection of the San Luis Obispo Valley basin using COMSOL Multiphysics 5.5 software. The goal of this project was to lay the foundation onto which a more robust model could be built and refined. Groundwater hydrology models of this area may already exist, but building a model using a finite element program has yet to be done, leaving room for a more accurate simulation tool. Going forward in a more water conscious era, it is paramount to utilize such tools to aid in management decisions.

The user-friendly interface that COMSOL offers and its ability to solve a series of differential and coupled equations makes it the ideal software to execute these important tasks. The learning curve for using COMSOL was less intense than other software which requires the user to have a knowledge of coding or scripting. The well refined user interface allows for a pleasant modeling experience and one which produces a product which the user can feel confident in.


