A WATER BALANCE AND SEDIMENT YIELD ANALYSIS MODEL FOR THE LOPEZ LAKE RESERVOIR

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Lee Joon Faraca
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TITLE: A Water Balance and Sediment Yield Analysis Model for the Lopez Lake Reservoir

AUTHOR: Lee Joon Faraca

DATE SUBMITTED: June 8th 2020

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

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

COMMITTEE MEMBER: Amr El Badawy, Ph.D.
Assistant Professor of Civil and Environmental Engineering
ABSTRACT

A Water Balance and Sediment Yield Analysis Model for the Lopez Lake Reservoir

Lee Joon Faraca

Lopez Lake Reservoir is the primary source of potable water for the Cities of Arroyo Grande, Grover Beach, Pismo Beach, and to the Community Service Districts of Oceano and Avila Beach. In this study, a water balance and sediment yield analysis model was developed for the reservoir’s watershed. The model was used to estimate evaporation from the lake and to examine the effects of a wildfire on the reservoir. Evaporation and wildfire are dependent on variables that change on a spatial and temporal scale, making modeling challenging. The County of San Luis Obispo uses pan coefficients to estimate evapotranspiration losses from the reservoir. In this study, a water balance model was developed using a watershed model known as Soil and Water Assessment Tool, SWAT. Evaporation loss from the lake was calculated using the inflows simulated by the model, and other fluxes (e.g., water released for consumption to Arroyo Grande Creek, precipitation) that were obtained from the County of San Luis Obispo. The evaporation values estimated by the pan coefficient model were significantly higher than the water balance and the Penman-Monteith predictions. The Penman-Monteith method estimates seem more reasonable for the lake. SWAT was also used to simulate effects of a wildfire on sediment inflow and sediment yield into the reservoir for a year after a simulated fire. Results showed that sediment inflow rates increased by a factor of 3 following the simulated wildfire. Lopez Lake Reservoir’s capacity would be significantly affected by a wildfire. To improve the evaporation estimates it is recommended that the County of San Luis Obispo install streamflow gauges to measure the inflow into the reservoir. Using the streamflow gauges the reservoir evaporation could be calculated using the water balance method. Adding climate gauges at the reservoir would increase the accuracy of the Penman-Monteith method. Sediment gauges in the watershed would provide a calibration data source for the model as well as data collection points in the event of an actual wildfire.
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Chapter 1

INTRODUCTION

Lopez Lake Reservoir is located ten miles east of the City of Arroyo Grande, in central coast of California. The reservoir has a total capacity of 49,200 acre-feet and has a 67 square mile watershed. It is formed by an earth-filled dam built in 1969. The dam is operated by the San Luis Obispo County Flood Control and Water Conservation District (2004 Water Quality Report Zone 3 – Lopez Project, 2004).

Reliable estimation of evaporation losses is important for effective operation and management of the lake. California’s drought problems reinforces the necessity of understanding the quantity of water lost in the supply system including to evaporation. Water resource managers are looking to reduce these losses, for example, by investing in water saving methods such as black polyethylene shade covers (Alvarez et al., 2006). Without accurate evaporation estimation, the benefit of such water saving efforts cannot be quantified. The County of San Luis Obispo estimates evaporation losses using a pan evaporation station near the lake. The pan coefficient evaporation method is generally considered the least accurate method at estimating evaporation (Grayson, 1996).

Generally, quantifying evaporation losses in the arid and semi-arid regions of the western United States have been inconsistent and inaccurate. The pan coefficient method doesn’t account for reservoir depth and uses a limited mass transfer method (Friedrich et al., 2018).

The county monitors the downstream releases and pipeline diversion from Lopez lake, and measures water levels of the reservoir using a monometer system. A combination of the monometer depth reading and data from a 2002 Bathymetric Survey are used to
calculate volume of water in the lake. The precipitation is measured at the Lopez Lake Dam using a rain gauge. The precipitation value and the 2002 Bathymetric Survey data are used to determine the increase in reservoir volume due to rain. Then, the pan-evaporation method is used with the water balance equation to calculate inflows to the lake from the watershed (Lopez Lake Operation Data, 2020). Since the county uses the pan coefficient evaporation estimation in their water balance equation, any inaccuracies with the evaporation estimation will carry over to the reservoir inflows. If the reservoir inflows are not accurate, then the reservoir cannot be managed properly. Mismanaging a reservoir, especially during a drought can cause unnecessary strain on groundwater resources (Shukla et al., 2015). Water scarcity has become the greatest threat to food security, human health, and natural ecosystems, thus, understanding the losses in a reservoir is necessary for these times ahead (Seckler et al., 1999).

In this study, a watershed simulation model was developed for the Lopez Lake Reservoir watershed and was used to simulate inflows to the lake. Evaporation from the lake was then calculated using the water balance equation as well as the Penman-Monteith equation, and was compared to the county’s pan coefficient based evaporation estimates. The comparison will help to examine the accuracy of the method used by the county.

Another key objective of this study was to estimate sediment yield and sediment inflow before and after a hypothetical wildfire in the watershed. Wildfires have become larger and more frequent across the western United States (Miller and Safford, 2012). Climate change models indicate that the risk of large wildfires in California will increase between 12% to 53% by 2099 (Westerling and Bryant, 2008). Extreme weather variability caused by climate change (Swain et al., 2018), will worsen the damage caused by the “fire and
flood cycle” (Cannon and DeGraff, 2009). The components of water balance for a reservoir (i.e., inflows and outflows) are sensitive to climate and land use changes (Xu et al., 2009). Landscape that is burned has a diminished ability to capture, filter, and regulate water to streams. Previous studies have showed that runoff and erosion can increase by up to several orders of magnitude following a wildfire (Katimbo et al., 2018). Understanding the magnitude of sediment yield, with and without wildfire, is important for Lopez Lake Reservoir management. The runoff and erosion will change the sediment inflow rates into the reservoir. Reliable estimation of sediment inflow is essential as it is often needed to estimate the amount of pollutants flowing into a reservoir. The change in sediment inflow will affect the storage capacity of the reservoir until the watershed has recovered from the fire. The increased runoff and erosion commonly last between 3-8 years after a wildfire, depending on the watershed. Watershed recovery rate has been found to be most dependent on the pre-fire vegetation, landscape slope, wildfire burn intensity, and post-fire soil hydrophobicity (Warrick et al., 2012). Lopez Lake Reservoir is a critical infrastructure for the communities it is serving. This study will provide predictive estimates of sediment yield values post wildfire, which the County of San Luis Obispo could use to improve their response to a wildfire.
Chapter 2

LITERATURE REVIEW

2.1 Evapotranspiration

Evapotranspiration (ET) is the loss of water due to both surface evaporation and plant transpiration (Ukkola and Prentice, 2013). ET is a major component of the water balance and an important factor in reservoir planning and management. ET is affected by many factors such as, solar radiation, air temperature, humidity, wind speed, plant type, plant variety, plant density, plant growth stage, soil conditions, water salinity, and even plant pests/disease. Quantifying ET accurately is nearly impossible due to the spatial and temporal variability of the factors that affect ET (Temesgen et al., 2005). However, depending on location, data access, and required accuracy of calculation, different methods are used to calculate ET (Zhao et al., 2013). There are four commonly used methods of estimating evapotranspiration: pan coefficient, water balance, energy balance, and mass transfer. The pan coefficients method uses data from local pan evaporations to estimate ET. The method is often used for irrigation scheduling and water resources planning (Snyder et al., 2005). The water balance method estimates ET as the function of water inflow, water outflow, and change in storage over a set control volume, and is commonly used at a monthly, seasonal, or annual temporal scale (Jensen, 2010). The energy balance method is similar to the water balance method but it analyzes the system in terms of energy inflow and outflow, instead of water inflow and outflow. This method takes into consideration the physical properties such as solar radiation, latent heat flux, and the heat capacity of the water to estimate ET (Bello and Smith, 1990). Mass transfer methods utilize the concept of eddy motion transfer of water vapor from the evaporating
surface to the atmosphere. All the equations are based on Dalton’s Law, however, the wide ranging inconsistency in meteorological data collection procedures and standards have led rise to over 100 mass transfer evaporation equations (Singh and Xu, 1997).

Calculating ET using pan coefficients is a common practice for calculating water loss from lakes or from crops (Linacre, 1994). In the United States, pan evaporation estimates come from field measurements made using the National Weather Service’s Class A evaporation pan, which is a standardized stainless steel pan 10 inches in height and 47.5 inches in diameter. A still well with a high quality evaporation micrometer or automatic evaporation sensor is used to measure the evaporation. The still well prevents rippling of the water surface, increasing the accuracy of the evaporation sensor. To measure evaporation, the Class A evaporation pan is placed in the field. The field should have an unobstructed area with a natural air flow. Next the pan is filled with a known volume of water. After a standardized time period, usually 24 hours, the water volume is measured. Any precipitation values are taken into consideration. The difference between the initial and final volume of water is the pan evaporation. The class A pan evaporation (i.e., $E_{pan}$) has been consistently greater than the free water evaporation from a shallow lake (Eagleman, 1967). As a result, evaporation from nearby water bodies is calculated as,

$$ET = K_{pan} \times E_{pan}$$

(Eq. 1)

Where: 

- $ET$ = Evapotranspiration 
- $K_{pan}$ = Pan evaporation correction coefficient 
- $E_{pan}$ = Pan evaporation
$K_{\text{pan}}$ depends on the type of pan used, the field environment, humidity, and wind speed (Eijkelkamp, 2009). Even with the correction, pan coefficients are found to give estimates that are too high especially in arid regions (Morton, 1979). However, another study found that Pan-Coefficients work well in arid climate of California. Adjustments would likely be needed for humid or more windier climates (Snyder et al., 2005). These findings support the notion that estimating ET with reasonable accuracy is difficult due to the complexity of the process and its variability over time and space. Table 1 shows the Pan-Coefficients used by the County. The Pan-Coefficients were determined experimentally by an evaporation measuring station located near the Lopez Lake Reservoir.

### Table 1. San Luis Obispo County Lopez Lake Reservoir Pan-Coefficients

<table>
<thead>
<tr>
<th>Month</th>
<th>Pan Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.64</td>
</tr>
<tr>
<td>February</td>
<td>0.64</td>
</tr>
<tr>
<td>March</td>
<td>0.67</td>
</tr>
<tr>
<td>April</td>
<td>0.71</td>
</tr>
<tr>
<td>May</td>
<td>0.74</td>
</tr>
<tr>
<td>June</td>
<td>0.77</td>
</tr>
<tr>
<td>July</td>
<td>0.80</td>
</tr>
<tr>
<td>August</td>
<td>0.80</td>
</tr>
<tr>
<td>September</td>
<td>0.80</td>
</tr>
<tr>
<td>October</td>
<td>0.79</td>
</tr>
<tr>
<td>November</td>
<td>0.76</td>
</tr>
<tr>
<td>December</td>
<td>0.67</td>
</tr>
</tbody>
</table>
2.2 Water Balance

The water balance method analyzes a control volume of water through water fluxes and storage changes. Water flux quantifies the inflows and outflows of water in the control volume. Precipitation, groundwater recharge, surface runoff, subsurface runoff, and ET are the typical water flux variables considered in the water balance equation. The change in storage is due to soil-water storage changes, snow and ice changes, groundwater changes, and reservoir stage changes (Senay et al., 2011). The water balance method is mathematically described as,

\[ P + \sum Q - D - AET = \Delta S \]  

(Eq. 2)

Where:

- \( P \) = Precipitation
- \( \sum Q \) = Sum of inflows and outflows for the control volume
- \( D \) = Groundwater recharge/percolation
- \( AET \) = Actual evapotranspiration
- \( \Delta S \) = Change in storage

Water balances are most often used to determine a variable that is hard to quantify such as ET or groundwater recharge (Domingo, 2001). Streamflow gages and weather sensors collect inflow, outflow, and precipitation data. Geographical models of the reservoir provide storage data. The total loss, which includes groundwater recharge/percolation and ET is calculated (Senay et al., 2011). SWAT has been used to minimize the difference between basin-wide model simulated ET and remote sensing-based ET from the surface energy balance algorithm (Bastiaanssen et al., 1998). In this study, the water balance equation was used to estimate evaporation for Lopez lake.
2.3 Penman-Monteith Method

Penman-Monteith method is a surface conductance-based combined mass transfer and energy balance model for evapotranspiration. This method incorporates the effects of both vegetation physiology and evaporation demand. ET is estimated by calculating the available energy to the minimum energy required for ET to occur. It requires atmospheric, physical, and solar data to calculate ET. The Penman-Monteith method assumes a “big leaf” or single-layer of coverage (Yang et al., 2012). Penman-Monteith method is more sensitive to aerodynamic and canopy resistance than to climatic differences. During the summer period, when ET values are high, the input variables are highly sensitive during the daytime (Beven, 1979). The Penman-Monteith method has been found to correlate well for hourly and daily time steps within California for estimating ET (Temesgen et al., 2005).

2.4 Effect of Wildfire on Sediment Yield and Sediment Inflow

Wildfires cause changes in soil and watershed processes that increase stormwater runoff and sedimentation (Ice et al., 2004). They reduce evapotranspiration, increase soil’s repellency to water, decrease the critical shear stress required for soil erosion, destroy forest litter, and remove surface obstructions, which alter time to concentration values (Moody and Martin, 2004). This results in increase in sediment yield and greater peak discharge. A study of sediment yields from coastal California wildfires found that the wildfires play an important forcing factor in sediment yield values. The study found that sediment yields are often underestimated, and that sediment yields were an order of magnitude higher when followed by heavy precipitation (Warrick et al., 2012). Lopez Lake Reservoir is at risk for a wildfire followed by heavy rain. The summer dry season is
prone to wildfires, which is then followed by the rains of the wet season. There is a projected 25%-100% increase in extreme dry-to-wet precipitation events in California, indicating an increase in wildfire and heavy rain risks (Swain et al., 2018). A study in New Mexico found an average increase of 9.0 tons of sediment per hectare a year after a wildfire in a reservoir. The increase sediment yield decreased over the years, going from 5.2 t/ha/yr the second year, to 2.1 t/ha/yr the third year, 0.74 t/ha/yr the fourth year, to 0.67 t/ha/yr the fifth year (Reneau et al., 2007). A popular wildfire modeling method is to increase the curve numbers (CNs) by 5, 10, and 15 to represent a low, moderate, and high burn area (Higginson and Jarnecke, 2007). However, there is no consistent methodology to estimate post-fire CN values. Each watershed has a different hydrological response and will recover in a different manner. The recovery and response of a watershed is linked to the types of vegetation present, their rate of recovery, and fire severity. Most wildfire simulations do not have extensive field data. For sediment yield, the first year, post-fire, is simulated. Trends show the first year, post-fire will have the highest sediment yield values during a normal recovery period (Leopardi and Scorzini, 2015).
Chapter 3

DATA AND METHODOLOGY

3.1 Data and Methodology Overview

The methodology section outlines the creation, calibration, and analysis of the evaporation and wildfire scenarios for the model. It also outlines the methodology and reasoning for each input used. Figure 1 shows a graphic representation and summary of the methodology section.

Figure 1. ET, Sediment Yield, and Sediment Inflow Methodology and Process Flowchart
3.2 Overview of SWAT

ArcSWAT, an ArcMap extension of SWAT (Soil and Water Assessment Tool), was used to create a model for the Lopez Lake Reservoir watershed. The program simulates the hydrological cycle through a continuous time model using climatology data. There are two divisions to the hydrological cycle, the first division is the land phase and the second division is the routing phase. The land phase controls the amount of water, sediment, nutrient, and pesticide loadings to reaches. The routing phase determines the movement of water, sediments, nutrients, and pesticides through the reach network to the watershed outlet. SWAT divided the watershed into different subbasins. Each subbasin consists of hydrologic response units (HRU) and a reach. SWAT uses topography, soil, land cover, and weather data to analyze a watershed to create HRU’s. Each HRU is made up of a unique combination of variables and contributes a different loading value to a reach. Every subbasin has a single, main reach which routes the land phase loading values to the watershed outlet. Flow velocity was modeled with Manning’s equation; routing was with Muskingum Routing Method. Each reach was assumed to have a trapezoidal channel geometry with 2:1 side slope. Flow is routed through the reach network to the watershed outlet (Neitsch, 2005).

3.3 SWAT Model Creation

A 5m resolution Digital Elevation Model (DEM) of San Luis Obispo County was used to define the hydrology of the model. SWAT used this DEM to delineate the watershed boundary, subbasin areas, streams, and outfall locations. Figure 2 displays the geographic location of Lopez Lake Reservoir.
Figure 2. Lopez Lake Reservoir Location Map
The HRU’s were created by ArcSWAT. ArcSWAT has a US soil database which was used to classify the soils and create HRU’s within the subbasins. For this study, 953 HRU’s were created for the watershed. The HRU’s were defined using the multiple HRU option so that each HRU would contribute their unique values to the land phase. The U.S. Geological Survey’s 2016 National Land Cover Database (NLCD) was used to define the land use. The NLCD map was clipped to the watershed size, and then defined using the ArcSWAT 2016 NLCD look up table. Figure 3 shows the land cover and land use data generated by the NLCD. Soil data was downloaded from the United States Department of Agriculture (USDA) web soil survey database. The soil data for San Luis Obispo County was downloaded and clipped to fit the watershed. Figure 4 shows the soils data created. A single slope class was used to create the HRU. This implies that the subbasins were disaggregated into 953 HURs based on soil and land use only. The slope data from the 5m DEM is shown in Figure 5. Given that the model must run monthly simulations for 10 years, it was concluded that a single slope class would facilitate model simplicity. The HRUs represent heterogeneity in slopes and other watershed characteristics well.
Figure 3. Lopez Lake Reservoir Watershed Land Use Land Cover Map
Figure 4. Lopez Lake Reservoir Watershed Soil Map
Figure 5. San Luis Obispo 5m DEM Map
Precipitation data was pulled from the National Oceanic & Atmospheric Administration (NOAA) climate database. The NOAA station ID:GHCND:USC00047851, located at the California Polytechnic State University San Luis Obispo (Cal Poly) campus provided all the data. The California Irrigation Management Information System (CIMIS) supplied the temperature, solar radiation, wind, and relative humidity information. CIMIS data is from Station 52, which is also located on the Cal Poly campus. SWAT’S WGEN First Order weather simulator was used to simulate and fill missing weather data.

Initial rainfall data came from the NOAA Cal Poly station. During calibration, a hand calculated water balance found that there were issues with the weather data. The precipitation values were not consistent with the ET values that the model was calculating. A comparison of precipitation values from the NOAA Cal Poly station, NOAA Nipomo station, and the Lopez Lake Dam sensor, in Table 1, confirmed the rainfall variability from station to station.

**Table 2. Rainfall Comparison Table**

<table>
<thead>
<tr>
<th>Date</th>
<th>Nipomo (in)</th>
<th>Cal Poly (in)</th>
<th>Lopez Lake (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>24.900</td>
<td>41.450</td>
<td>51.040</td>
</tr>
<tr>
<td>1996</td>
<td>18.090</td>
<td>18.090</td>
<td>37.630</td>
</tr>
<tr>
<td>1997</td>
<td>11.470</td>
<td>29.700</td>
<td>60.670</td>
</tr>
<tr>
<td>1998</td>
<td>28.240</td>
<td>31.180</td>
<td>45.520</td>
</tr>
<tr>
<td>1999</td>
<td>11.770</td>
<td>15.330</td>
<td>52.314</td>
</tr>
<tr>
<td>2000</td>
<td>14.010</td>
<td>30.980</td>
<td>51.190</td>
</tr>
<tr>
<td>2001</td>
<td>14.660</td>
<td>27.100</td>
<td>51.080</td>
</tr>
<tr>
<td>2002</td>
<td>9.210</td>
<td>18.080</td>
<td>49.570</td>
</tr>
<tr>
<td>2003</td>
<td>8.520</td>
<td>16.810</td>
<td>49.520</td>
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<td>2004</td>
<td>11.610</td>
<td>32.580</td>
<td>51.310</td>
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<tr>
<td>2005</td>
<td>16.440</td>
<td>14.120</td>
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<tr>
<td>2006</td>
<td>15.250</td>
<td>14.770</td>
<td>45.529</td>
</tr>
</tbody>
</table>
A map of the NOAA stations and the Lopez Lake Dam sensor is shown in Figure 8. Table 1 shows that rainfall values are location dependent. In a mountainous watershed, precipitation values throughout the area have been shown to vary greatly (Tsintikidis et al., 2002). This variance indicates that the weather data inclusive of precipitation, relative humidity, solar radiation, and wind, may not be accurate. Using the Lopez Lake Dam precipitation data will result in a more accurate representation than the Cal Poly NOAA station data. However, it will not compensate for the precipitation variability within the watershed. Since the Lopez Lake Dam operations does not have sensors for temperature, relative humidity, solar radiation, and/or wind, no corrections were applied to the rest of the weather data. The consequences of using this uncorrected data must be considered during results analysis.

Figure 6. Precipitation Station Locations
Thirteen years of all-weather data, including daily temperature, precipitation, wind speed, relative humidity, and solar radiation were formatted and imported into SWAT. The weather data starts from January 1st, 1994 and ends on December 31st, 2006. SWAT was run for 10 years of simulation with a 3-year warmup period where model simulations are used to diffuse the impact of initial conditions on model predictions. The years 1994, 1995, and 1996 were the warm-up years, and the model results from 1997-2006 were used for analysis. Monthly time steps were used for the analysis.

3.4 Evapotranspiration Loss Comparison Overview

SWAT was used to calculate ET using a water balance and the Penman-Monteith method. Both the water balance and Penman-Monteith method use different variables to estimate ET. Results from these methods were compared to the ET estimated by the pan coefficient method.

3.4.1 Estimating ET Using Water Balance

A water balance equation was used to calculate evaporation from Lopez Lake Reservoir. Equation 3 is the water balance equation that the County of San Luis Obispo uses.

\[ Q_{in} = E + Q_{out} - P + \Delta C + \Delta S \]  

(Eq. 3)

Where:

- \( E \) = Evaporation
- \( P \) = Precipitation
- \( Q_{in} \) = Stream Inflow
- \( Q_{out} \) = Stream Outflow
- \( \Delta C \) = Change in Storage Volume in the Reservoir
- \( \Delta S \) = Change in Storage Volume due to Groundwater Seepage
\( \Delta S \) is assumed to be negligible as the reservoir was built in 1969. Years of sediment will have built up on the bottom of the reservoir, making groundwater losses insignificant. 

\( Q_{out} \) is the sum of the downstream release, pipeline diversion, and spillway discharge. 

The County of San Luis Obispo has sensors that measure \( Q_{out} \), precipitation data, and lake capacity. Pan coefficients are used to estimate the evaporation from the lake. The measured and/or estimated values of \( E, P, Q_{out}, \) and \( \Delta C \) values from April 1968 to March 2019 were provided in the County of San Luis Obispo Dam Operations Data Excel sheet. 

The County of San Luis Obispo uses the water balance method outlined in Equation 3 to calculate \( Q_{in} \). There are no streamflow gages at the entrance to the reservoir, so the County of San Luis Obispo must calculate the inflows. Equation 3 was rearranged into Equation 4 to estimate evaporation in the reservoir.

\[
E = (Q_{in} - Q_{out}) + P - \Delta C - \Delta S \tag{Eq. 4}
\]

Where: 
- \( E \) = Evaporation
- \( P \) = Precipitation
- \( Q_{in} \) = Stream Inflow
- \( Q_{out} \) = Stream Outflow
- \( \Delta C \) = Change in Storage Volume in the Reservoir
- \( \Delta S \) = Change in Storage Volume due to Groundwater Seepage

Evaporation is estimated using a combination of the County of San Luis Obispo Dam Operations Data and the SWAT model. \( Q_{in} \), the reservoir inflow will be simulated using the SWAT model. The same \( P, Q_{out}, \) and \( \Delta C \) used in Equation 3 will be used in Equation 4. Evaporation was then calculated as a function of the Dam Operations Data and the SWAT model. The SWAT model provides the inflows that the County of San Luis
Obispo calculated, and the Dam Operations Data provides $P$, $Q_{out}$, and $\Delta C$. Using Equation 4 the average monthly evaporation from Lopez Lake Reservoir was calculated.

### 3.4.2 Estimating ET Using Penman-Monteith Method

SWAT uses the Penman-Monteith Method to estimate ET. Penman-Monteith Method accounts for the energy needed to sustain evaporation, the strength of the mechanism required to remove the water vapor and aerodynamic and surface resistance terms. This method uses solar radiation, air temperature, relative humidity, and wind speed data to estimate evapotranspiration.

$$\lambda E = \frac{\Delta (H_{net} - G) + \rho_{air} + C_p \left( e_0^z - e_z \right)}{\Delta + \gamma \left( 1 + \frac{r_c}{r_a} \right)}$$

(Eq. 5.)

Where:

- $\lambda E$ = Latent Heat Flux Density
- $E$ = Rate of Evaporation
- $\Delta$ = Slope of the Saturation Vapor-Pressure-Temperature Curve
- $H_{net}$ = Net Radiation
- $\rho_{air}$ = Air Density
- $C_p$ = Specific Heat at Constant Pressure
- $e_0^z$ = Saturation Pressure of Air at Height $Z$
- $\gamma$ = Psychometric Constant
- $r_c$ = Plant Canopy Resistance
- $r_a$ = Diffusion Resistance of the Air Layer

Using this equation ArcSWAT calculates the ET in units of mm (Neitsch, 2005). The ET is found using the ET data from the HRU’s from the subbasins that the reservoir is located in. For subbasins 11, 12, 13, and 14, the ET depths from the HRU’s defined as
water were multiplied by their area. The sum of all the ET from the water in these subbasins is the Penman-Monteith ET estimation for the Lopez Lake Reservoir.

### 3.5 Modeling Changes due to Wildfire

Modeling wildfires is difficult. Topography, soil conditions, vegetation condition, wind direction, and wind speed play important roles in fire spread and direction. These factors vary on a temporal and spatial scale. These factors will affect the severity and damage caused by the fire. To model the effects of wildfire, the CN properties of the model were altered to represent conditions after a wildfire (Cova et al., 2005).

Wildfire model simulations that use SWAT generally model just the year following the wildfire. Havel, Katimbo, and Rodrigues, all used SWAT to evaluate conditions of the year following a wildfire (Havel, 2015) (Katimbo et al., 2018) (Rodrigues et al., 2019). The first year after a fire will have the greatest erosion and runoff values. Watershed recovery rates differ, varying between 3-8 years, making it hard to accurately model without field data (Warrick et al., 2012). In this study, both sediment inflow and sediment yield were calculated for a year following the simulated wildfire. This wildfire was simulated to have happened on 1/1/1996, after the 3 year warm up period. The CN values will be increased to a post-fire representation. This SWAT model has been calibrated on flow data but has not been calibrated with any sediment data. Therefore, during analysis, the magnitudes of the sediment yield were compared.

The San Luis Obispo 2017 Burn Severity map was used to determine the post-fire CN increase of each subbasin. San Luis Obispo’s Burn Severity map was derived from the
California Department of Forest and Fire Protection (CAL FIRE) Burn Severity Map shown in Figure 7. Figure 8 shows the burn severities from the San Luis Obispo County 2017 Burn Severity Map georeferenced into SWAT. The burn map is created by the County based on vegetation density, slope severity, and other relevant factors. Table 3 describes each burn severity.

**Table 3. Burn Severity Description Table**

<table>
<thead>
<tr>
<th>Burn Severity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Severity</td>
<td>Surface organic layers are not completely consumed and roots are generally unchanged, due to minimal heat penetration of the soil. While exposed mineral soil may appear lightly charred, the canopy and understory vegetation generally appears unchanged.</td>
</tr>
<tr>
<td>Moderate Severity</td>
<td>Up to eighty percent of the pre-fire ground cover may be consumed. Roots may be scorched but generally not completely consumed, and soil structure is unchanged.</td>
</tr>
<tr>
<td>High Severity</td>
<td>All or nearly all of the pre-fire ground cover is generally consumed, along with roots up to 0.1 inches in diameter. Charring may be visible on larger roots. Significant bare or ash covered soil is exposed and soil structure is less stable due to loss of root mass.</td>
</tr>
<tr>
<td>Very High Severity</td>
<td>Local government delineated areas of high severity fire that require special land management/building codes and requirements. Land cover changes due to wildfire are the same as a high severity.</td>
</tr>
</tbody>
</table>

*Table descriptions from (Moore, 2016) and (Very High Fire Hazard Severity Zones)*

A very high severity zone has the same CN increase as a high severity zone. Very high severity zones are California Government Code Section 51179 required local government delineated areas (California Department of Forestry). These areas are identified by local
government to retard the rate of fire spread. Very high severity zones have land management/building codes and requirements to prevent fire spread to populated or dangerous areas (Very High Fire Hazard Severity Zones). Therefore, it was assumed that the CN changes due to a very high severity fire will be the same as a high severity fire. The rate of fire will change, but the damages are assumed to be the same as high severity fires. Grey areas in Figure 8, indicate that the Federal Government is responsible for managing these areas. These areas align with the burn severity jurisdictions outlined by California Department of Forest and Fire Protection (CAL FIRE) in Figure 7. Therefore, these areas indicate jurisdiction not severity, and since each grey area is enclosed and surrounded by very high severity areas, the grey areas are assumed to also be very high severity zones.

Figure 7. CAL FIRE San Luis Obispo County Burn Severity Map
Figure 8. 2017 San Luis Obispo Burn Severity Map With Subbasin Labels
The increase in CN per subbasin was found using a composite CN value, shown in equation 6, based on burn severity areas. ArcMap watershed and geometry tools were used to find the areas of each.

\[
CN_c = \frac{\sum_i^n(CN_i \cdot A_i)}{\sum_i^n(A_i)}
\]  
(Eq. 6)

Where: 
- \( CN_c \) = Composite CN of the Entire Watershed 
- \( CN_i \) = Composite CN of the Burn Severity Classification Area 
- \( A_i \) = Area of the Burn Severity Classification Area

Table 4 shows the composite CN increase for each subbasin.

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Area (ft²) of Fire Severity by Subbasin</th>
<th>Composite CN Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>None</td>
<td>Moderate</td>
</tr>
<tr>
<td>1</td>
<td>332224875</td>
<td>6756667</td>
</tr>
<tr>
<td>2</td>
<td>8736533</td>
<td>69070396</td>
</tr>
<tr>
<td>3</td>
<td>37567760</td>
<td>69497241</td>
</tr>
<tr>
<td>4</td>
<td>71559314</td>
<td>1338403</td>
</tr>
<tr>
<td>5</td>
<td>3890601</td>
<td>17069724</td>
</tr>
<tr>
<td>6</td>
<td>3697067</td>
<td>20969007</td>
</tr>
<tr>
<td>7</td>
<td>3804454</td>
<td>6950697</td>
</tr>
<tr>
<td>8</td>
<td>38510260</td>
<td>13907333</td>
</tr>
<tr>
<td>9</td>
<td>4458814</td>
<td>6238894</td>
</tr>
<tr>
<td>10</td>
<td>11376953</td>
<td>8217894</td>
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<tr>
<td>11</td>
<td>10135905</td>
<td>11628177</td>
</tr>
<tr>
<td>12</td>
<td>4734483</td>
<td>1693613</td>
</tr>
<tr>
<td>13</td>
<td>7248415</td>
<td>6705785</td>
</tr>
<tr>
<td>14</td>
<td>2058918</td>
<td>33761907</td>
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<tr>
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<td>1582393</td>
<td>3734686</td>
</tr>
<tr>
<td>20</td>
<td>14893096</td>
<td>79227104</td>
</tr>
</tbody>
</table>

Table 4. Composite CN Increase per Subbasin by Type of Fire Severity

<table>
<thead>
<tr>
<th>CN Increase</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>15</td>
</tr>
<tr>
<td>Moderate</td>
<td>10</td>
</tr>
<tr>
<td>High</td>
<td>15</td>
</tr>
<tr>
<td>Very High</td>
<td>15</td>
</tr>
</tbody>
</table>
There is limited literature on vegetation survival rates from a wildfire, but plenty of studies exist on the mortality rates of vegetation following a fire. Wildfire conduction, convection, radiation, combustion, fire plumes, and heat transfer to soil, can kill a tree. Trees that survive the wildfires may perish due to heat induced cell necrosis. Wildfires with intense crown fires, at the base of the plant, generally kill the entire plant (Michaletz and Johnson, 2007). A wildfire with intense crown fire is assumed for this study, as it has the highest plant mortality rate. This will model a worst-case scenario wildfire.
Chapter 4

CALIBRATION

4.1 Calibration Overview

SWAT Calibration and Uncertainty Procedures (SWAT CUP), a calibration program, was used to calibrate the model by altering ArcSWAT model parameters. A parameter is any characteristic used to define the runoff, groundwater, soil properties, and contaminant movement within the model. Examples of parameters are snowmelt ratio, land cover coefficient, rate of evapotranspiration, soil hydraulic conductivity, HRU slope, average channel width, initial nitrogen concentration, etc. SWAT CUP can calibrate a reach, subbasin, and/or HRU output file from ArcSWAT to observed data. The program uses SUFI2, a sequential uncertainty fitting approach and few other algorithms to calibrate the model. SUFI2, which was selected for this study, starts with a large parameter value range, and with each iteration narrows the parameter range, while monitoring the P-factor and R-factor. Parameters can be changed relative to the initial values or can be replaced. A relative range becomes a multiplier value applied to the original parameter. A replace value is directly substituted for the original value. The program aims to calibrate the model output to the observed output by modifying the parameters and produces the likely (best) estimation as well as the within a 95% prediction uncertainty (95PPU). In this study, SWAT CUP was set to run for one thousand iterations. One thousand iterations were considered sufficient for convergence. SWAT CUP analyzes every iteration and choses the best parameter set based on the objective function value. The Nasch-Sutcliffe (NS) efficiency factor was used as the objective function.

Maximize: \[ NS = 1 - \frac{\sum (Q_m - Q_s)^2}{\sum (Q_m - \bar{Q_m})^2} \] 

(Eq. 7)
Where: \( Q_m \) = Measured Variable  
\( Q_s \) = Simulated Variable  
\( \bar{Q}_m \) = Average of the Measured Variable

The NS objective function is sensitive to significant over- or-under prediction (Neitsch, 2000). It works well for defining data with high peaks and is a common objective function used when modeling flood prediction. This objective function suits the variable, high peak flows of the wet/dry San Luis Obispo County weather well (Krause et al., 2005). An NS value of > 0.5 indicates that a model has been sufficiently calibrated. A calibrated NS value > 0.65 indicates a well calibrated model. The closer the NS values is to 1, the more accurate the model is (Ritter and Muñoz-Carpena, 2013).

4.2 Calibration Data Sources

One set of observed data was used to calibrate the model. The data set came from the United States Geological Survey (USGS). This data set had daily average values for streamflow. These streamflow values were used to calibrate the reach output files from SWAT. The data set was assigned a location on a reach for calibration purposes. Daily data was compiled into a monthly average value. Ten years of monthly data were used for calibration, creating 120 data points of observed values. These observed values started on January 1st, 1997 and ended on December 31st, 2006.

USGS has a streamflow gage located in subbasin 11 as shown in Figure 11. This gage provided average daily streamflow values. It was assumed that the inflow into reach 11 in subbasin 11 was the same value as measured with the USGS gage. It is not a perfect assumption. The streamflow gage is located in the upstream portion of the subbasin,
making inflow a better assumption than an outflow value. Only subbasins 1, 2, 3, and 4 contribute streamflow to subbasin 11, where reach 11 is. Therefore, when calibrating for reach 11, the subbasins whose parameters were altered were 1, 2, 3, 4, and 11. Since there is only one data set for calibration, the calibrated parameters for subbasins 1, 2, 3, 4, and 11 were applied to all subbasins.

Figure 9. Stream Gage, Subbasin, and Reach Map of Lopez Lake Reservoir, CA
4.3 Calibration Process

ArcSWAT has a built-in model examiner called SWAT Checker. SWAT Checker analyzes the output files from the simulation. It creates warnings for potential problems. Before calibrating the model, SWAT Checker was used as a reference to identify possible problems with the model. Figure 8, warns that the groundwater ratio may be low, lateral flow is greater than groundwater flow, and that the water yield may be excessive. The ET/precipitation value of the model is 35%, which is low. ET/precipitation values should be at least 50-60%. Changing the groundwater, land cover, and runoff coefficient variables, helped calibrate the ET/precipitation values.

![SWAT Checker Hydrology Summary, Messages, and Warnings](image)

**Figure 10. SWAT Checker Hydrology Summary, Messages, and Warnings**

For the initial calibration attempt, the precipitation data used in the ArcSWAT model was from the NOAA Cal Poly station. The Cal Poly station was used for weather data. It was assumed that this data would be accurate enough to use. During the initial calibration,
the following seven parameters were changed. These parameters were chosen based on the results from SWAT Checker to increase ET/precipitation.

1. Initial SCS runoff curve number (CN2.mgt)
2. Baseflow alpha factor (ALPHA_BF.gw)
3. Groundwater delay (GW_Delay.gw)
4. Threshold depth of water in the shallow aquifer required for return flow to occur (GWQMIN.gw)
5. Available water capacity of the soil layer (SOL_AWC.sol)
6. Saturated Hydraulic Conductivity (SOL_K.sol)
7. Moist Bulk Density (SOL_BD.sol).

Figure 11 displays the 95PPU plot of reach 11. The red, best estimation line, and the blue, observed data line, do not match. Peak flow values are either under or over estimated. Flow values from the 60-120 mark on the x-axis are order of magnitudes higher than the observed data. The NS value of the initial calibration attempt was -2.23. An NS value of 0.50 or above indicates a sufficient calibration (Ritter and Muñoz-Carpena, 2013). This calibration attempt indicated that more parameters needed to be considered, as the NS value was far from acceptable.
Figure 11. Initial Calibration Attempt Reach 11 SWAT CUP 95PPU Plot
For the second calibration attempt, nineteen parameters were used to calibrate the model.

1. Initial SCS runoff curve number (CN2.mgt)
2. Baseflow alpha factor (ALPHA_BF.gw)
3. Groundwater delay (GW_Delay.gw)
4. Threshold depth of water in the shallow aquifer required for return flow to occur (GWQMIN.gw)
5. Available water capacity of the soil layer (SOL_AWC.sol)
6. Saturated Hydraulic Conductivity (SOL_K.sol)
7. Moist Bulk Density (SOL_BD.sol).
8. HRU soil evaporation compensation factor (ESCO.hru)
9. Average subbasin slope length (SLSUBBSN.hru)
10. Average tributary channels (CH_S(1).sub)
11. Tributary channel Manning’s “n” (CH_N(1)).sub)
12. Average HRU slope steepness (HRU_SLP.hru)
13. Moist soil albedo (SOL_ALB(top layer).sol)
14. Groundwater revap coefficient (GW_REVAP.gw)
15. Deep aquifer percolation fraction (RCHRG_DP.gw)
16. Manning’s “n” value for overland flow (OV_N.hru)
17. Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur (REVAPMN.gw)
18. Plant evapo-transpiration curve number coefficient (CNCOEF.bsn)
19. Initial depth of water in the deep aquifer (DEEPST.gw)
These nineteen parameters are related to peak flow and time of concentration. The parameters will help expand the possible range of the 95PPU, creating a better calibration. Figure 12 shows the 95PPU plot of the second calibration attempt.

Figure 12. Second Calibration Attempt Reach 11 SWAT CUP 95PPU Plot
Additional parameters increased the range of the 95PPU, but the calibration curve does not represent the observed data. The 95PPU range follows the general shape of the observed data but the timing and magnitude of the peak flow values are wrong. Calibrated peak flows are magnitudes lower than the largest observed peak flows. The calibrated peak flow apex occurs after the observed peak flow apex, indicating an issue with the time of concentration estimate. Despite calibration with nineteen parameters, the NS value is 0.08. The precipitation data for the Cal Poly NOAA Station, the Nipomo NOAA Station, and the Lopez Lake Rain gauge were compared. As seen in Figure 12, the model inflows were lower than the observed inflows. For the third calibration attempt the precipitation data from Lopez Lake Dam, instead of the Cal Poly NOAA Station were used, as that data set had the highest precipitation values. The larger precipitation values will help increase the model inflows. Figure 13, shows the results of the third calibration attempt for reach 11.
Figure 13. Third Calibration Attempt Reach 11 SWAT CUP 95PPU Plot

The third calibration attempt had an NS value of 0.62, above the targeted 0.5 value, and was deemed sufficiently calibrated. Table 5 on the following page has a list of all the calibrated values.
Table 5. Subbasin Calibration Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum Parameter Value</th>
<th>Maximum Parameter Value</th>
<th>Calibrated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN2.mgt</td>
<td>-1</td>
<td>1</td>
<td>-0.165</td>
</tr>
<tr>
<td>ALPHA_BF</td>
<td>0</td>
<td>1</td>
<td>0.574</td>
</tr>
<tr>
<td>GW_DELAY.gw</td>
<td>30</td>
<td>3000</td>
<td>2042.175</td>
</tr>
<tr>
<td>GWQMN.gw</td>
<td>0</td>
<td>5000</td>
<td>4287.5</td>
</tr>
<tr>
<td>SOL_AWC.sol</td>
<td>-0.7</td>
<td>0.9</td>
<td>-0.238</td>
</tr>
<tr>
<td>SOL_K.sol</td>
<td>-0.9</td>
<td>0.9</td>
<td>-0.314</td>
</tr>
<tr>
<td>SOL_BD.sol</td>
<td>-0.9</td>
<td>0</td>
<td>1.998</td>
</tr>
<tr>
<td>SLSSUBBSN.hru</td>
<td>10</td>
<td>150</td>
<td>273.450</td>
</tr>
<tr>
<td>CH_S1.sub</td>
<td>0</td>
<td>0.8</td>
<td>0.034</td>
</tr>
<tr>
<td>CH_N1.sub</td>
<td>0.01</td>
<td>0.2</td>
<td>0.087</td>
</tr>
<tr>
<td>HRU_SLP.hru</td>
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<td>0.6</td>
<td>0.567</td>
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<tr>
<td>ESCO.hru</td>
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<td>0.630</td>
</tr>
<tr>
<td>EPCO.hru</td>
<td>0.01</td>
<td>1</td>
<td>0.724</td>
</tr>
<tr>
<td>SOL_ALB().sol</td>
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<td>1</td>
<td>0.814</td>
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<tr>
<td>GW_REVAP.gw</td>
<td>0</td>
<td>1</td>
<td>0.696</td>
</tr>
<tr>
<td>RCHRG_DP.gw</td>
<td>0</td>
<td>1</td>
<td>0.594</td>
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<td>OV_N.hru</td>
<td>0.005</td>
<td>0.6</td>
<td>0.383</td>
</tr>
<tr>
<td>REVAPMN.gw</td>
<td>0</td>
<td>1000</td>
<td>238.5</td>
</tr>
<tr>
<td>DEEPST.GW</td>
<td>0</td>
<td>5000</td>
<td>3862.5</td>
</tr>
</tbody>
</table>

Italic indicate replace values, normal text indicates relative values
Chapter 5

RESULTS AND DISCUSSION

5.1 Results Overview

The results of the ET Pan-Coefficient, water balance, and Penman-Monteith method comparison, the pre and post-fire sediment yield, and the pre and post-fire inflows are presented and discussed in this section. For the results comparison, the SWAT output files were imported to Excel. The data were formatted into both tables and graphs. Results were compared using both the graphs and tables. Tables were used to compare metrics while the graphs were used to identify trends and patterns.

5.2 Evapotranspiration

Figure 14 shows the comparison of ET values. The comparison includes the county Pan-Coefficient determined ET, the SWAT Penman-Monteith mass transfer-energy balance ET, and the ET from the water balance method.
Figure 14. Average Daily ET For Lopez Lake Reservoir, CA Using Different ET Methods

All three methods have the same seasonal trend, with the peak ET values in the summer months, and the lowest ET values in the winter months. However, both the shape and the magnitude of the ET values vary by method. The Pan-Coefficient method has a higher estimation of ET than the water balance or Penman-Monteith method. On average the Pan-Coefficient method peaks are 1.30 times higher than the Penman-Monteith method and 5.61 times higher than the water balance method. Both the Pan-Coefficient and Penman-Monteith methods have a similar graphical shape. The Pan-Coefficient method has higher peak values 9 out of the 10 times. These higher peaks result in a greater volume of ET. The findings support the study that Pan-Coefficients method overestimates ET in arid regions (Morton, 1979). They also support the idea that the actual ET value is
not being accurately represented by the Pan-Coefficient method. It is important to note that during the water balance analysis, twenty-six of the one hundred and twenty water balance ET values were negative when calculated. They are represented in Figure 14 as a value of 0. A negative ET indicates that during this month, the inflow values were larger than the outflow values. ET cannot be a negative value, negative values indicate that there was an increase in storage. Since the increase in storage volume in the reservoir was greater than the ET volume, the water balance method returned a negative ET value. The majority of the negative values happen during the winter when the storage is expected to increase. Calibration using just the USGS streamflow gauge may not have provided adequate calibration for the entire subbasin. These negative ET values could also indicate that the assumption that the calibration parameters of reach 11 cannot be applied to the rest of the watershed. Therefore, the most trustworthy ET estimate of these three methods, is the Penman-Monteith method, which has been found to estimate ET well in California (Temesgen et al., 2005).
5.3 Wildfire Effect on Sediment Yield

Figure 15. Pre-Fire and Post-Fire Sediment Inflow Graph

Table 6. Sediment Inflow Table

<table>
<thead>
<tr>
<th>Date</th>
<th>Pre-Fire Sediment Inflow (tons/month)</th>
<th>Post-Fire Sediment Inflow (tons/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-97</td>
<td>15350.00</td>
<td>45940.00</td>
</tr>
<tr>
<td>Feb-97</td>
<td>197.20</td>
<td>22.14</td>
</tr>
<tr>
<td>Mar-97</td>
<td>85.21</td>
<td>3.95</td>
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<tr>
<td>Apr-97</td>
<td>7.31</td>
<td>3.71</td>
</tr>
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<td>May-97</td>
<td>0.01</td>
<td>3.54</td>
</tr>
<tr>
<td>Jun-97</td>
<td>0.00</td>
<td>3.48</td>
</tr>
<tr>
<td>Jul-97</td>
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<td>Dec-97</td>
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<td>3407.00</td>
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</tbody>
</table>
The sediment inflow increased after the simulated wildfire. The “baseflow” rate of sediment inflow increased 5.28 times from pre-fire average value of 0.72 tons per month to post-fire average value of 3.80 tons per month. Table 6 shows that a 2.99 times increase in sediment inflow was measured in January 1997, with sediment inflow increasing from 15350 to 45940 tons per month. Figure 15 shows the changes in sediment inflow due to wildfire. The shape of the sediment yield and inflow graphs changed due to the simulated wildfire. Post-fire sediment peak inflows were shorter in duration and higher in value than the pre-fire. A rainfall event after a wildfire will cause a larger volume of sediment to enter the reservoir over a shorter period of time. The magnitude increase in sediment inflow and the following increase in the “baseflow” sediment inflow will decrease the capacity of the reservoir. These “baseflow” sediment inflow changes will affect the hydrological cycle and will result in changes to channel morphology, which will change the channel geometry, path, and flow rates into the reservoir (Xu et al., 2009).

Depending on the severity of the sediment inflow increase, the capacity of the reservoir could be significantly decreased. The County of San Luis Obispo needs to be aware of the potential impacts of a wildfire’s effect on sediment inflow in the reservoir. Lopez Lake Reservoir is a critical piece of water infrastructure to for the Cities of Arroyo Grande, Grover Beach, Pismo Beach, and to the Community Service Districts of Oceano and Avila Beach. Modeling the first year after a wildfire provides an important perspective on forecasting the effects on the reservoir and watershed. Understanding the possible effects of a wildfire can help the County of San Luis Obispo prepare for a disaster, and minimize the impacts.
6.1 Conclusions

The SWAT model had just one set of measured data used for calibration with NS values of 0.62. These NS values are on the lower end of the confidence interval, just surpassing the 0.5 minimum threshold. The assumption that the calibrated parameters for reach 11 can be applied to the entire subbasin added inaccuracy to model. More accurate weather inputs would help increase the NS value, improving the models results. This model was effective in comparing ET values, as well as estimating the changes to sediment yield and sediment inflow due to a simulated wildfire, two difficult to model subjects. Both ET and wildfire are difficult to model because each are determined by variables that change of a spatial and temporal scale.

The County of San Luis Obispo’s ET estimates are based on the Pan-Coefficient method. This method calculated ET values that were consistently higher than the water balance and the Penman-Monteith method. Both the water balance and Penman-Monteith method estimated ET values 5.61 and 1.30 times lower than the Pan-Coefficient method. This model supported the findings that the Pan-Coefficient method overestimates ET in arid regions (Morton, 1979). Since the County of San Luis Obispo uses a water balance to calculate inflow, and their ET values are inaccurate, so are the inflow values. The ET is overestimated which means the inflow into the reservoir is being underestimated. Given that ET was negative in some cases when calculating ET using the water balance, the Penman-Monteith method is the most reliable method for estimating ET in this area. The
Penman-Monteith method uses meteorological data, which when used in small time steps, such as a daily or hourly time step, represents the evaporation well in an arid climate. Applying the reach 11 calibrated parameters to the entire model did not accurately simulate the actual inflow into the reservoir. In the winter months, when the storage increased, the water balance method calculated negative ET estimates. Even though the NS value of the calibrated reach was 0.62, the model is having trouble modeling the inflows during periods of high precipitation. It is hypothesized that since the model inflows were not the same as the County of San Luis Obispo inflow values that the change in storage values from Equation 3 would not be the same for the simulated SWAT model and the Dam Operations Data. Therefore, since the change in storage values were not updated to match the model inflows, the water balance calculation returned negative values during some months.

Sediment inflow hydrograph geometry changed due to wildfire. The first month after the wildfire, sediment inflow increased by a factor of 2.99, and the “baseflow” of sediment inflow increased to by a factor of 5.28. Sediment yield increased an order of magnitude during the first month post-fire. Despite having no sediment calibration data, these results seem reasonable, and align with past field studies. Wildfire creates a significant increase in sediment inflow and yield within a watershed.

**6.2 Recommendations**

The model can be improved by using more accurate input data. Solar radiation, wind speed, temperature, and relative humidity were measured at the Cal Poly CIMIS station, while the precipitation was measured at the reservoir. Placing weather sensors at the lake
and using those measurements would provide more accurate data. If sensors are not viable, transformation and adjustments on the CIMIS station weather data should be made so that the data more accurately represents the Lopez Lake Reservoir watershed.

For a high confidence ET estimate, flow gages should be placed in the streams that contribute to the reservoir. From the County of San Luis Obispo Dam Operations Data, the ET could be calculated using the water balance and the new streamflow gages. Values used in this water balance calculation would all be from measured sources, resulting in an accurate ET estimate. These flow gages could also be used as a second calibration point, increasing the accuracy of the model.

To improve the sediment yield and inflow part of the model, calibration data is needed. Sediment data could be measured or calculated. Field measurements of sediment data on a set basis each month for a year would provide sufficient data. The more frequent the testing, the better representation of sediment flows there will be, especially after storms. Sediment inflow and yield could also be measured in the reservoir. The amount of additional sediment built up in the reservoir could be used to calibrate reach 20. Finally, sediment inflow and yield could be calculate based on change in reservoir storage capacity. This method would be less accurate than measurement. Also, sediment gauges would also collect sediment data in the event of an actual wildfire. This data would be important in determining fire severity and the watershed recovery.
ArcSWAT can be used to model wildfire over a temporal scale. It would be an intensive process that would require field testing, extensive literature review, and an expert understanding of how ArcSWAT works. Through yearly land use updates, the land use and land cover characteristics could be changed. A field test or literature review for each land use and land cover type would dictate the recovery rate of each classification. The land use updates would have to be applied for every land use and land cover type in each HRU in each subbasin.
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