Quantifying Climate Change Impacts to City of Santa Barbara Water Supplies

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Client: The City of Santa Barbara Public Works

March 2020

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Re-envisioning.

A Group Project submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science & Management for the Bren School of Environmental Science & Management

Acknowledgements

The team would like to thank everyone who supported our project. We would like to extend our deepest gratitude to the following people:

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Allison Horst, Lecturer (Bren School of Environmental Science & Management)
Max Moritz, Adjunct Professor (Bren School of Environmental Science & Management)
Kelley Dyer, Assistant General Manager (Casitas Municipal Water District)
Shawn Johnson, Senior Hydrologist (Santa Barbara County - Public Works Department)
Jason White, Project Manager (South Coast Habitat Restoration)

Funding Provided By: James S. Bower Foundation

Photo Credit
Title Page Photo: City of Santa Barbara Public Works

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Acronyms

AAT - All-At-A-Time
AET - Actual Evapotranspiration
AF - Acre-Feet
AFD - Acre-Feet Per Day
AFY - Acre-Feet Per Year
BAER - Burned Area Emergency Response
CCWA - Central Coast Water Authority
CFS - Cubic Feet Per Second
CMIP5 - Coupled Model Intercomparison Project Phase 5
COMB - Cachuma Operations and Maintenance Board
CO_2 - Carbon Dioxide
DEM - Digital Elevation Model
°F - Degree Fahrenheit
DWR - Department of Water Resources
FRAP - Fire and Resource Assessment Program
GCM - Global Climate Model
GHG - Greenhouse Gas
GIS - Geographic Information System
GSAs - Groundwater Sustainability Agencies
GSPs - Groundwater Sustainability Plans
H++ - Extreme Sea-Level Rise Scenario
HRUs - Hydrologic Response Units
kWh - Kilowatt Hours
LOCA - Localized Constructed Analogs
mm - Millimeters
NLCD - National Land Cover Database
NOAA - National Oceanic and Atmospheric Administration
NTU - Nephelometric Turbidity Units
OAT - One-At-A-Time
PET - Potential Evapotranspiration
RCPs - Representative Concentration Pathways
SBFTM - Santa Barbara Flow and Transport Model
SGMA - Sustainable Groundwater Management Act
STATSGO2 - Digital General Soil Map of the United States
SWAT - Soil and Water Assessment Tool
SWAT-CUP - Soil and Water Assessment Tool Calibration and Uncertainty Program
SWP - State Water Project
SYR - Santa Ynez River
USDA - United States Department of Agriculture

USEPA - United States Environmental Protection Agency
USGS - United States Geological Survey
USYROA - Upper Santa Ynez River Operations Agreement

Abstract

Climate change affects water supply through changes in precipitation, temperature, and evapotranspiration. The City of Santa Barbara's water supply relies largely on water held in Lake Cachuma and Gibraltar Reservoir, located in the upper Santa Ynez River watershed. Quantifying climate change impacts to this watershed is critical to planning for future water supply. This project modeled the potential impacts of climate change on the Santa Ynez River watershed out to 2058 using the Soil and Water Assessment Tool. The model was calibrated using meteorological and streamflow data for the upper Santa Ynez River watershed. Future streamflow was then simulated for the high-emissions scenario (RCP 8.5) using five global climate models which produce a range of possible futures for California. The simulated streamflow was evaluated to estimate a range of future upper Santa Ynez River watershed inflows to Lake Cachuma under the different climate simulations. The results of the drought model simulation indicate: (1) a projected decrease of approximately 40% in average streamflow and (2) a decrease in the contribution of the upper Santa Ynez River watershed to Lake Cachuma by as much as a factor of 2 compared to the historical baseline. Compared to the historical baseline, the other four climate conditions that were simulated produced changes in average streamflow, from -20% to +20%, and upper Santa Ynez River watershed contributions to Lake Cachuma, from 0% to +20%. The results from the simulations will inform the City of Santa Barbara's water supply planning out to 2050.

Purpose

The City of Santa Barbara (City) relies mainly on water held in Lake Cachuma and Gibraltar Reservoir, which is supplied by the Santa Ynez River watershed (SYR). The City is aware that the effects of climate change, including potential changes to precipitation, temperature, and the length and intensity of droughts, will affect their future water supply. However, the existing 2011 Long Term Water Supply Plan (LTWSP) does not quantify climate change impacts to the surficial water supply. To maintain a reliable surficial water supply under a changing climate, the City must anticipate potential future impacts to the SYR watershed.

The objectives of this project are to: (1) synthesize historical SYR watershed supply data; (2) model historical streamflow for the SYR watershed using the hydrological Soil and Water Assessment Tool (SWAT); and (3) simulate impacts of climate change on local surface water availability up to 2058 using downscaled precipitation and temperature projections from five global climate models (GCMs). Compiling and synthesizing historical SYR watershed supply data allowed for assessment of the watershed's contribution to the City's water resources. Modeling historical streamflow for the SYR watershed using SWAT allowed for calibration of the model before incorporating climate change projections. Finally, SWAT was used to explore potential climate change impacts on surface water availability up to 2058 through the use of downscaled precipitation and temperature projections.

Residents of Santa Barbara and nearby cities may use the project's forecasts of future water supply, coupled with the modeled climate change impacts on water supply, to understand the region's future availability of water. Having reliable, affordable, and safe access to water is a pressing concern in southern California, especially as climate change continues to put pressure on the water supply by increasing the frequency of droughts or floods. This project is expected to help the City determine the range of availability of water for residents of Santa Barbara in the near future, enabling City planners and residents to prepare for a future water supply impacted by climate change.

Significance

Average water use in California falls within three main sectors: environment[1] (50%), agriculture (40%), and urban (10%) (Mount & Hanak 2019). Water allocation between these sectors differs significantly between wet and dry years. Urban water use has declined overall despite California's growing population. Statewide, per capita water use in urban areas decreased from 231 to 180 gallons per day from 1990 to 2010 (Mount & Hanak 2019). Key urban conservation efforts include household water efficient appliances, leak detection in the water distribution system, landscape water conservation programs, and consistent water metering (Water Education Foundation 2020). Statewide conservation efforts are reflected in the California Water Plan, which works to ensure access to high quality water resources for future generations (California Department of Water Resources 2017).

The City provides water to a ~20 square mile service area supporting ~93,000 people (Water Resources Division 2015). The City of Santa Barbara Public Works Department has been working to adapt their water portfolio to account for future growth and climate change impacts. Though the City has a current LTWSP, the implications of climate change on water supply sources and storage infrastructure necessitate further study and adaptive planning.

The City's Climate Action Plan projects an average temperature increase of 1.8 - 5.4 degrees Fahrenheit; a 12 - 35%[2] decrease in overall rainfall with increasingly erratic, more extreme weather events; greater risk of seawater intrusion into aquifers; and greater risk of wildfires in southern California (City of Santa Barbara 2012). The Climate Action Plan uses precipitation projections from a Scripps Institute of Oceanography study[3] focusing on the San Diego area. The study results are relevant to Santa Barbara as the San Diego area also shares a mediterrenean climate with highly variable precipitation rates (The San Diego Foundation 2008). The SBA CEVA, a local ecosystem vulnerability assessment report, projected that under the RCP 8.5 emissions scenario, annual precipitation will reduce by 9%[4] by 2050 (Myers et al. 2017). The differences in precipitation projections reflect differences among the models and between San Diego and Santa Barbara as well other uncertainties in the data and models.

Greater variability in rainfall as a result of climate change may affect future streamflow within the SYR watershed. This can have implications for inflow to SYR watershed's surficial reservoirs. In

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[1] Environmental water is defined as water in rivers protected as "wild and scenic" under federal and state laws, water required for maintaining river and stream habitats, water used to support wetlands, and the water required to maintain water quality for agricultural and urban use (Mount & Hanak 2019).

[2] The Scripps Institute of Oceanography ran six climate simulations for the San Diego area using three climate models (GFDL CM2.1, CMRM CM3, NCAR CCSM3). Three simulations projected that precipitation will decrease by 12-35%. While three simulations projected that precipitation will increase by 12-17% (The San Diego Foundation 2008).

[3] The San Diego Foundation Regional Focus 2050 Study published by the San Diego Foundation.

[4] The SBA CEVA report used statistically downscaled output from 10 global climate models (ACCESS1-0, CanESM2, CCSM4, CESM1-BGC, CMCC-CMS, CNRM-CM5, GFDL-CM3, HadGEM2-CC, HadGEM2-ES, and MIROC5) to project future precipitation (Myers et al. 2017).

addition, future increases in extreme precipitation events and wildfire frequency have the potential to exacerbate sedimentation within the SYR watershed's reservoirs, Cachuma and Gibraltar. Sediment accumulation within Gibraltar and Cachuma results in less water storage capacity, constraining the City's water resources.

To prepare for localized climate change impacts, the City seeks a more detailed analysis incorporating results from existing climate change models scaled down to Santa Barbara County. This analysis will consider variability of streamflow into surface reservoirs and contextualize the impacts of wildfires and the subsequent increased sediment load on reservoir capacity.

By establishing a range of potential reductions to the City's local surface water sources, the City can estimate a water supply gap between its anticipated future water demand and potential water availability. This estimated water supply gap could be incorporated into the City's next Long-Term Water Supply Plan, which will cover the period through 2050. As climate change impacts availability of existing supplies, reliable long-term water supply may require exploring the feasibility of expanding current water sources or finding new opportunities for the City's supply, storage and conservation efforts. Santa Barbara's planned methods for securing long term water supply can serve as an example for other coastal cities interested in predicting future supply gaps and exploring new potential water supplies and management strategies.

Chapter 1. Background

1.1 City of Santa Barbara Water Overview

The City has a diverse water supply portfolio spanning five distinct sources, and the amount of water used from each source varies by year. In average to wet years, the City relies on surface water from Cachuma and Gibraltar reservoirs. In extended drought periods, when surface water supplies are limited, the City relies on increased groundwater pumping, imported water from the State Water Project, desalination, and conservation efforts. Figure 1 shows the City's supply mixtures from 2005 to 2018.

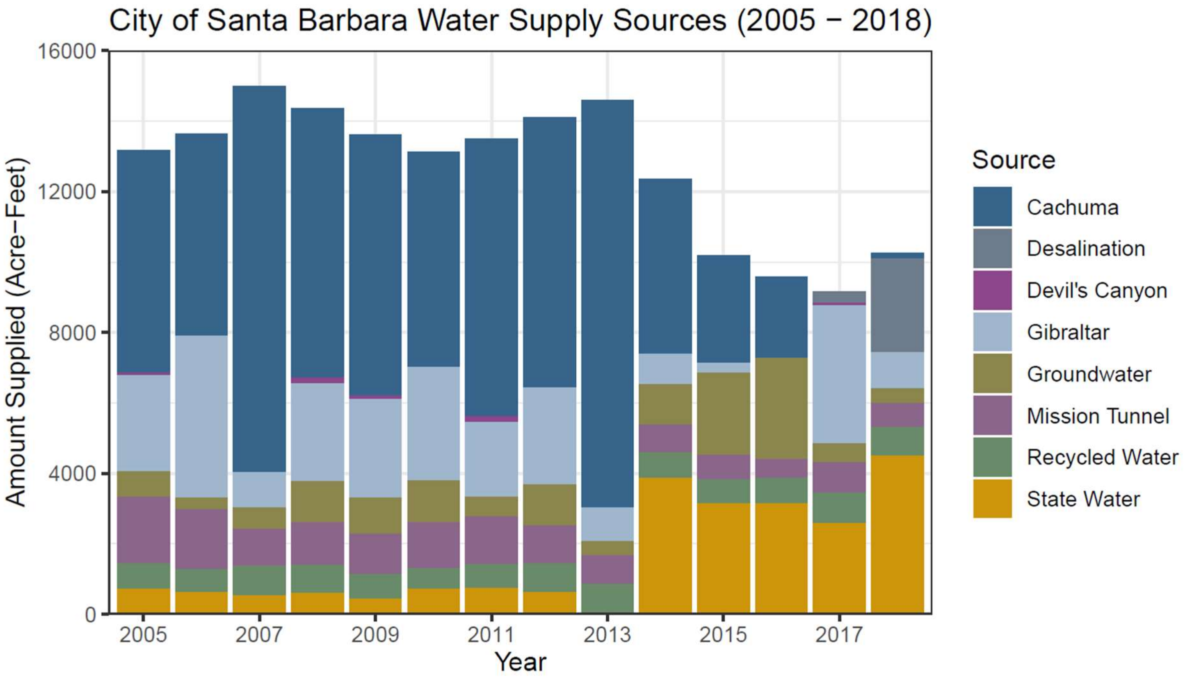


Figure 1. City of Santa Barbara water supply mix (acre-feet) from 2005 - 2018. Devil's Canyon Creek diverts water from Gibraltar into Mission Tunnel to supplement water from Gibraltar during periods of high turbidity. Water seeping through Mission Tunnel is considered a groundwater source. Data source: City of Santa Barbara Public Works Department.

The City defines three stages of drought: Stage One is to alert the public of potential water shortages; Stage Two reflects serious water shortages which include implementing water restrictions; and Stage Three is defined as extreme water shortages with more aggressive water restrictions (City of Santa Barbara Public Work Department Water Resources 2019). On May 12, 2015, the City entered a Stage Three Drought Condition in which drought water use regulations were implemented. During this time, drought had reduced potable water to approximately 10,600 acre-feet per year (AFY), a 30% reduction from pre-drought potable water demand (Analysis of Water Use for Development 2018).

After experiencing above average rainfall that increased surface water storage, the Santa Barbara City Council retracted Stage Three drought emergency conditions and adopted a Stage One water supply condition on April 9, 2019. In 2013, as California entered its latest period of drought, 86% of the City's water was supplied by the Gibraltar and Cachuma reservoirs (Figure 2). In 2018, 11% of water was supplied to the City by these two reservoirs and 44% was imported from the State Water Project, most likely due to the state being in the midst of a drought (Figure 3).

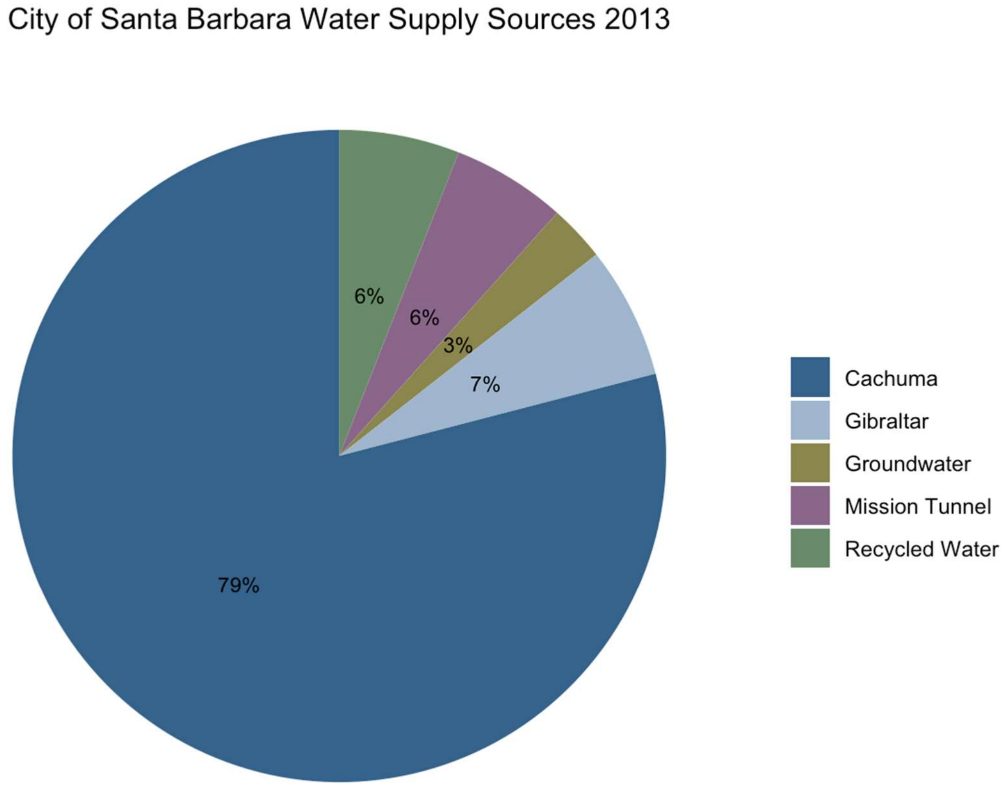


Figure 2. City of Santa Barbara water supply (acre-feet) in 2013 by source. Percentages indicate the proportion of water supplied from each source in 2013. Data source: City of Santa Barbara Public Works Department.

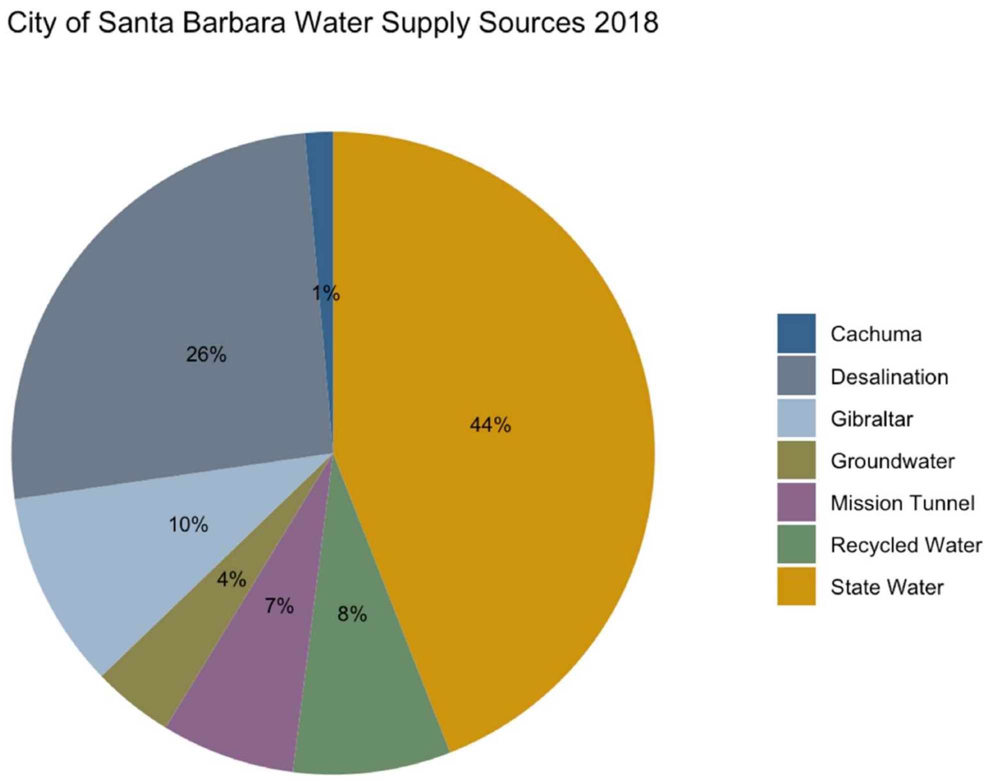


Figure 3. City of Santa Barbara water supply (acre-feet) in 2018 by source. Percentages indicate the proportion of water supplied from each source in 2018, which illustrates a drought year mixture. Data source: City of Santa Barbara Public Works Department.

Water demand for the City has been steadily declining since the late 1980s (Figure 4). For example, gross potable water use was 16,300 acre-feet (AF) in the late 1980s, decreased to 9,400 AF by 2016, and stabilized at 13,000 AFY under average, non-drought conditions (City of Santa Barbara 2019, Water Resources Division 2015). Water demand decreases during drought years due to conservation practices implemented by the City. These practices aim to improve water efficiency by reducing excessive water usage (Water Resources Division, Public Works Department 2011). The City is working to incorporate projected yearly water demand out to 2050 into their Enhanced Urban Water Management Plan, and long-term planning in general (Corey 2020).

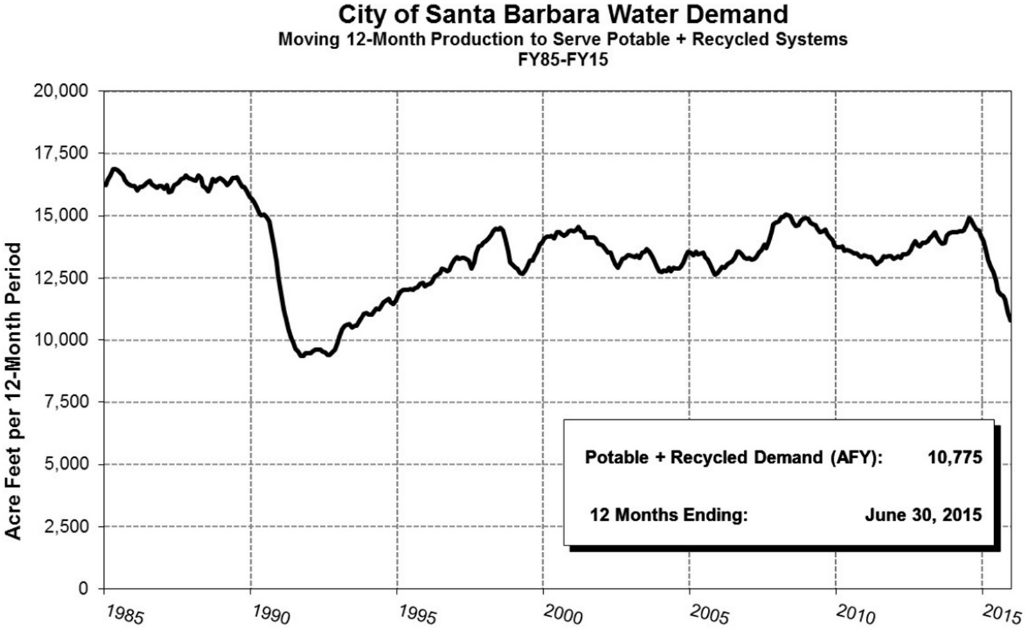


Figure 4. City of Santa Barbara water demand from 1985 to 2015. Consumer water demand has decreased since 2015. Source: City of Santa Barbara Urban Water Management Plan, 2015 Update.

1.2 Study Area

The City obtains a significant portion of its water from two surficial reservoirs: Lake Cachuma and Gibraltar. These reservoirs are fed by inflow from the SYR Watershed. It is located between the Santa Ynez and San Rafael Mountain Ranges (Santa Barbara County Conservation Blueprint Atlas 2017). The SYR is within the arid, mediterranean climate and California chaparral ecosystem of the San Rafael Mountains (RMC 2015).

Hydrology

The SYR headwaters begin at an elevation of approximately 4,000 feet and drain 900 square miles before meeting the Pacific Ocean (MNS Stetson Engineers Inc. 2013). The river flows west, from Los Padres National Forest through the Gibraltar Reservoir to the Cachuma Reservoir (CA Central Coast Regional Water Quality Board 2016). The water that flows through the system and reaches the Pacific is largely determined by anthropogenic uses and environmental flow requirements. The river's main tributaries include the Salsipuedes, Cachuma, Santa Cruz, and Indian creeks (Figure 5). During the rainy season, precipitation events result in large runoff events. During the dry season, surface flow is reduced, with intermittent flows.

The upper part of the SYR consists of bedrock scour pools scattered throughout the channel (Block & Francis 2013). This stream bed morphology contributes to the development of pool riffles and step pools along the river. Step pools, common in mountainous areas and important to channel dynamics, tend to form when stream bed materials are large in size and the width of the channel is relatively narrow (Chin 1989). Surveying by the California Department of Fish and Wildlife from 2010 to 2012 determined that more than 25% of stream channels within the Santa Cruz Creek in the Santa Ynez watershed consists of step pools (Block & Francis 2013).

In the 20th century, the SYR was modified by dams and reservoirs. The Gibraltar and Cachuma reservoirs are owned and operated by the City and the U.S. Bureau of Reclamation, respectively. The Tecolote Tunnel diverts river water stored in the Cachuma Reservoir to Santa Barbara. The designated beneficial uses for the river include municipal and domestic supply, groundwater recharge, cold freshwater habitat, and agricultural supply (CA Central Coast Regional Water Quality Board 2016).

Source Data
Flowlines and Reservoirs: High Resolution National Hydrography Dataset (U.S. Geological Survey, USEPA, USDA Forest Service, and other Federal State and Local Partners)
Dams and Coldwater Springs: U.S. Geological Survey, Geographic Information Name System.
Estuaries: U.S. Fish and Wildlife, 2004. National Wetlands Inventory.
Geothermal Springs: California Department of Conservation, Division of Oil and Gas, 2005. California Hot Springs database.

Figure 5. Hydrographic map of the Santa Ynez River. The river's main tributaries include the Salsipuedes, Cachuma, Santa Cruz, and Indian creeks. Source: California Central Coast Regional Water Quality Board 2016.

Geology

The SYR watershed is bordered to the south by the Santa Ynez Mountains and to the north by the San Rafael Mountains and Purisima Hills. The basin is intersected by the Foxen Canyon and Santa Ynez faults. Most of the geologic units in the basin are sedimentary: unconsolidated alluvium, sandstone, and mudstone (Upson & Thomasson 1951; Figure 6). In addition, there are igneous units in the eastern part of the basin. The sandstone and mudstone are of marine origin, deposited during the Jurassic period. The unconsolidated sedimentary deposits, which consist mostly of coarse gravel and sand, were deposited during the Tertiary period.

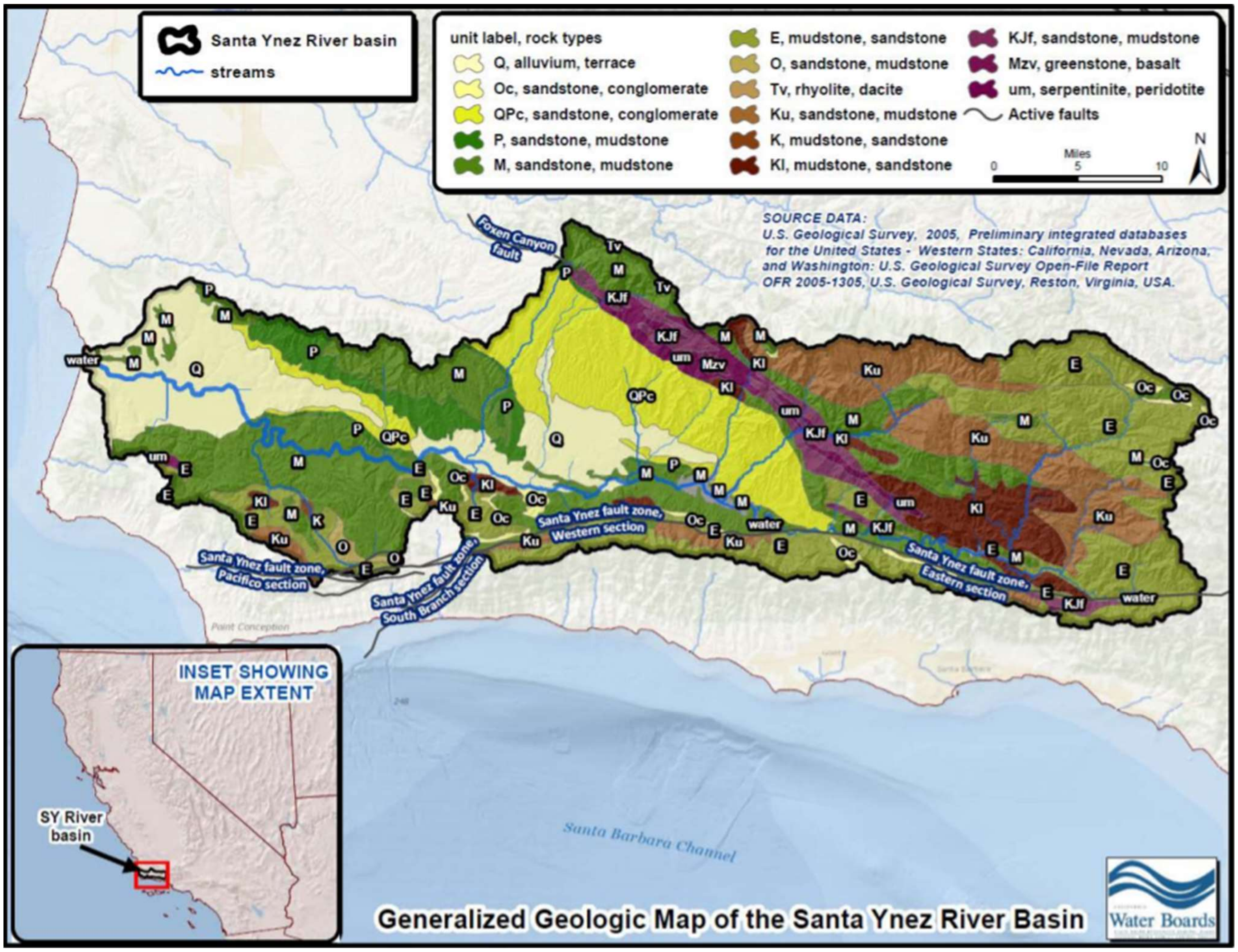


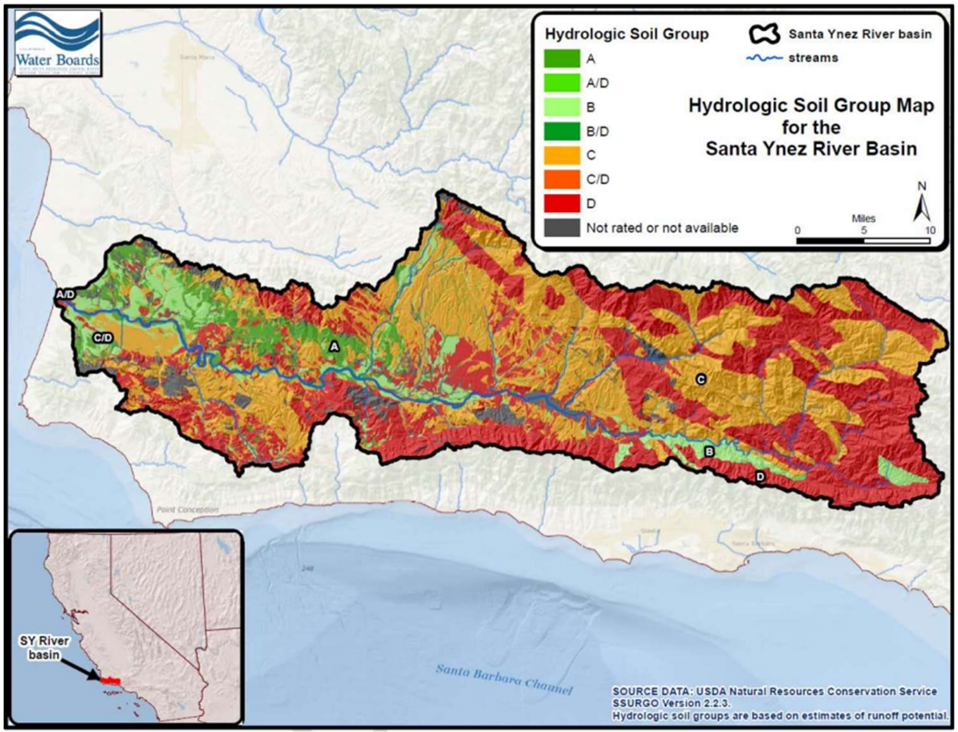
Figure 6. Geologic map of the Santa Ynez River Basin. Most of the basin's geology consists of sedimentary rocks. Source: California Central Coast Regional Water Quality Board 2016.

Soil

The US Department of Agriculture categorizes soil into hydrologic soil groups based on similar runoff potentials (Natural Resources Conservation Service 2007). Most of the soil located within the SYR watershed belongs to hydrologic soil groups C and D (CA Central Coast Regional Water Quality Board 2016; Figure 7). Soils within these groups have relatively slow infiltration rates when completely wet. They consist of fine-grained sediment and are mostly clays. Their clay composition explains the slow infiltration rates, as clays have high porosity, but low permeability.

Because the majority of the basin consists of clays, infiltration into groundwater likely occurs in the northwest region, where soil types A and B are located. Hydrologic soil group A has a high infiltration rate, consisting of sands and gravelly sands. Soil group B has a moderate infiltration rate, composed of sediments with moderately fine to coarse sand or loam.

The soils are eroded mostly by physical weathering via precipitation (Carpenter & Glassey 1927). During the rainy season from November to March, precipitation events may last hours. The intensity of this precipitation erodes the soil within this basin, especially the fine-grained sediments.



Hydrologic Soil Group Descriptions	
A	Well drained to excessively drained sands or gravelly sands.
B	Moderately well drained or well drained soils having moderately fine to moderately course texture.
C	Soils having a slow infiltration rate when thoroughly wet; moderately fine or fine texture.
D	Soils having a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays, soils which have a high water table, soils that have a claypan or clay layer near the surface, and soils that overlie a shallow, nearly impervious surface.
A/D	If a soil is assigned a dual hydrologic group, the first letter is for drained areas and the second is for undrained areas.

Figure 7. Hydrologic soil group map for the Santa Ynez River Basin. Most of the soils present in the basin have a relatively slow infiltration rate. Source: California Central Coast Regional Water Quality Board 2016.

Vegetation

The upper part of the SYR watershed encompasses Los Padres National Forest, in which there are six main types of vegetation. From greatest to least percent coverage, the vegetation within the forest consists of chaparral; pinion and juniper woodland; Coulter, Jeffrey, and Ponderosa Pine;

mixed evergreen and oak forest; oak woodland; and grassland (Block & Francis 2013). Chaparral has a dominant presence within Los Padres National Forest, as it is estimated to cover 68% of the area.

Riparian species dominate the lower region of the watershed, including western sycamore, coast live oak, poison oak, and other species (Block & Francis 2013). Together, these species contribute to a riparian composition that is less dense and provides less coverage than the vegetation present in the upper watershed. The lower watershed contains more non-native plants.

Evapotranspiration

Evapotranspiration is defined as the total evaporation and transpiration from land surfaces and plants (USGS 2018). Factors that affect evapotranspiration include humidity, wind speed, water availability, soil type, and plant type. Evapotranspiration is an important aspect of the hydrological cycle. Transpiration in mediterrenean climates can be restricted by a limited supply of water during the dry season and a limited supply of energy during the wet season (Turner 1991). Watersheds with a mediterrenean climate can also experience high water loss due to dense vegetation. The upper Santa Ynez watershed has a vegetation cover of 90% on the north-facing slopes, while the south-facing slopes have a 80% vegetation cover[5] (Turner 1991). Vegetation in the upper Santa River watershed has increased due to fire exclusion[6]. Between 1911 to 1986 average vegetation cover varied between 43 - 71% in the upper Santa Ynez watershed (Turner 1991). The estimated annual evapotranspiration rate for 800 acres of vegetation cover along the SYR[7] is 2,400 AF (Flores 2015). The estimated annual water loss due to evaporation for Lake Cachuma is 11,100 AF, Gibraltar Reservoir 1,200 AF, and Jameson Lake 494 AF (Flores 2015). Higher rates of evapotranspiration can potentially[8] increase if future temperatures rise due to climate change (North Carolina Climate Office n.d.).

Water Loss

The water distribution system for the City experiences water loss due to leaks in pipes and household meter issues (City of Santa Barbara Water Resources Division 2015). The 2015 Final Urban Water Management Plan states that monthly average water loss due to water distribution issues has been 11% of monthly water production (City of Santa Barbara Water Resources Division 2015). Monthly percentage of water loss was estimated by comparing the water distributed to the amount of water reaching consumers. Recent estimates as of 2019 estimate average monthly leakage at 95 AF per month (Corey 2020). The City uses American Water Works

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[5] The amount of shrub and tree cover present in the watershed (Turner 1991).

[6] Adopting fire suppressing plans allowing vegetation to accumulate (Keane et al. 2002).

[7] The Santa Ynez River flows through the Santa Ynez Valley from the Pacific Ocean to the upper Santa Ynez River watershed.

[8] There are many factors that affect evapotranspiration: humidity, temperature, water availability, wind speed, soil type and CO_2 concentrations. For example, increased humidity and higher CO_2 concentrations reduce transpiration negating the effect of temperature on evapotranspiration (Snyder et al. 2011) (North Carolina Climate Office n.d.).

Association water lost software to complete an annual water balance and participates in an audit to manage and account for water loss within the water distribution system (City of Santa Barbara Water Resources Division 2011). The City also has a water main replacement program that keeps track of broken water mains. The City currently replaces three miles of mains every year out of the 275 miles of mains within the distribution system (City of Santa Barbara Water Resources Division 2011).

1.3 Water Supply Sources

Gibraltar

Gibraltar Reservoir, owned and operated by the City, is an integral component of water supply and infrastructure, providing one-third of the City's water during average years (City of Santa Barbara 2020). Gibraltar Reservoir is filled by the SYR, draining 216 square miles of the watershed since its construction in 1920. Gibraltar Reservoir is 9 miles north of the City, and upstream of Lake Cachuma. In 1949, the dam was raised 23 feet in elevation to increase capacity because the reservoir had begun to fill with sediment. Although the reservoir was originally built with a capacity of 15,800 AF and despite the increase in capacity in 1949, it now holds only 4,300 AF due to sedimentation (MNS Engineers Inc. 2017). The long-term average yield is approximately 3,200 AFY (Stetson Engineers Inc. 2013, City of Santa Barbara Water Resources Division 2015).

Water from Gibraltar is currently carried to the City via Mission Tunnel (Figure 8). Diversions must abide by the 1930 Gin Chow agreement and the 1989 upper Santa Ynez River Operations Agreement (USYROA), otherwise known as the "Pass Through Agreement" (Holt 2016). This agreement is acknowledged by the U.S. Bureau of Reclamation and was created to avoid an additional enlargement of Gibraltar Dam. Under the agreement, water that would have been held at Gibraltar "base operations," "passes through" or is conveyed through Lake Cachuma (Stetson Engineers Inc. 2013, City of Santa Barbara Water Resources Division 2015). As sedimentation in Gibraltar constricts the City's "base operation" water use, "pass through" mode is used (Stetson Engineers Inc. 2013). Negotiations based on the Warren Act are ongoing, which would establish a preferred accounting mechanism for "base operations" at 8,600 AF or 1988 capacity assuming no sedimentation or excess spillover due to sedimentation (City of Santa Barbara Water Resources Division 2015).

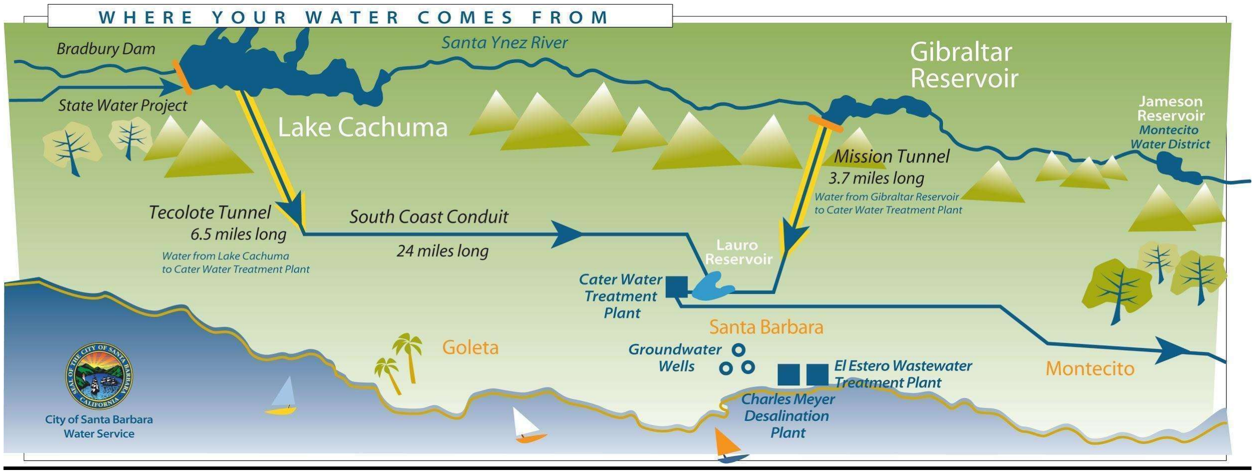

Figure 8. Schematic of the City of Santa Barbara's water sources and distribution. The City obtains water from Lake Cachuma via Tecolote Tunnel and water is routed from Gibraltar through Mission Tunnel. Source: City of Santa Barbara Public Works Department.

Constructed by 1911, Mission Tunnel was originally built to convey Devil's Canyon Creek water and Gibraltar Reservoir water to the City (City of Santa Barbara 2020). The City diverts Devil's Creek water to Mission Tunnel approximately 0.5 miles downstream of Gibraltar Dam. The City has pre-1914 water rights to divert from Devil's Creek and Gibraltar Reservoir. Diverted Devil's Creek water averages 120 AFY, and is of high quality. Devil's Creek supply has been used to improve the water quality of Gibraltar diversions, specifically to reduce turbidity after large storm events (City of Santa Barbara 2020). Gibraltar water is not diverted when turbidity exceeds 10 NTU[3], which occurs when inflow is greater than 1,000 acre-feet per day (AFD) or 500 cubic feet per second (CFS), halting diversions for 11 days. When flow rates exceed 5,000 AFD, diversions are halted for 31 days (Stetson Engineers Inc. 2013).

Mission Tunnel itself also acts as a groundwater source, as water seeping through the tunnel along its 3.7 miles contributes to an average yearly quantity of 1,100 AF (City of Santa Barbara 2019). Additional Mission Tunnel water is accounted for separately from Gibraltar diversions.

Lake Cachuma

Lake Cachuma, held by Bradbury Dam, is on average expected to yield 25,700 AFY in non-drought periods (City of Santa Barbara Water Resources Division 2015). Lake Cachuma is central to the City's water supply infrastructure and the other four Cachuma Member Units: Goleta Water District, Montecito Water District, Carpinteria Valley Water District, and the Santa Ynez River Water Conservation District (Stetson Engineers Inc. 2013). Built in 1953, Cachuma is 25 miles northwest of the City and drains 417 square miles (City of Santa Barbara 2020). Lake Cachuma's drainage basin also includes the upstream Gibraltar Reservoir and Jameson Reservoir, which are owned by the City and Montecito Water District, respectively.

The U.S. Bureau of Reclamation owns and operates the Cachuma Project to deliver water to the five Cachuma Member Units. The City is entitled to 32.19% of the Cachuma Project available water, or on average 8,300 AFY in average years (City of Santa Barbara 2020, City of Santa Barbara Water Resources Division 2015). Reclamation also operates Bradbury Dam for downstream water rights releases set forth in State Water Resources Control Board (SWRCB) Order WR 73-37 and amended WR 89-18.

At all times, flow requirements under the federal 2000 Biological Opinion must be met. Reclamation and the National Marine Fisheries Service have initiated a re-consultation process for a revised Biological Opinion, which could change future flow requirements and affect available water supply. While Lake Cachuma had an original capacity of 205,000 AF, due to storage loss through sedimentation, it now has a capacity of 190,000 AF with 5,900 AF allocated for fish habitat requirements (City of Santa Barbara Water Resources Division 2015, City of Santa Barbara 2019).

State Water Project

The State Water Project (SWP) delivers water into Lake Cachuma via the 103-mile Coastal Branch of the State Aqueduct, which connects to the 42 mile Santa Ynez Extension (Austin 2015). This imported water supply, quantified separately from the SYR catchment, is governed by the Central Coast Water Authority (CCWA). SWP water is delivered to Central Coast municipalities from Cachuma via the 6.4-mile Tecolote Tunnel and then through the 24-mile South Coast Conduit (Stetson Engineers Inc. 2013). Water infiltration into Tecolote Tunnel is also considered a supply source; however, it is included in total Cachuma allocations.

The City considers SWP water as a resource to be utilized during times of drought. The City is contracted for up to a 3,300 AFY allocation, including a 300 AFY "drought buffer," subject to water availability (City of Santa Barbara 2019). In theory, during years of water abundance the "drought buffer" would be provided in addition to a full SWP allocation and stored, potentially as groundwater, or used in lieu of groundwater pumping (United States Bureau of Reclamation 2004). Most years however, a full SWP allocation is not delivered and the "drought buffer" is effectively an additional supply that augments limited delivery and is used as part of the non-drought or normal allocation (Corey 2020). Allocations from the SWP vary from year to year, and have ranged from 5 to 85 percent in the recent drought.

Water Purchases

Facilitated through the CCWA, the City has also utilized supplemental water purchases delivered through the State Water Project during times of extended drought. Any supplemental water received through an exchange with another State Water Contractor requires that some of the water must be returned over time, which led to the accrual of "water debt" during the drought. This "water debt" must be returned, or taken out of the City's SWP allocation, during average years within a certain amount of time depending on specific agreements (City of Santa Barbara Water Resources Division 2015).

Groundwater

The City has three identified groundwater basins that are recharged[9] in average years and used to supplement surface water supply in drought years (City of Santa Barbara 2020). Storage Unit 1, beneath downtown Santa Barbara, produces on average 800 AFY. The Foothill Basin, underlying the upper State Street area, produces on average 900 AFY, 450 AFY for private wells and 450 AFY to City supply (City of Santa Barbara Water Resources Division 2015). Both basins provide approximately 1,300 of sustainable production, with no overdraft[10] (City of SB Long Term Water Plan 2011). Storage Unit 3, underneath the Westside area, has limited production potential due to poor water quality (City of Santa Barbara 2020). However, Unit 3 is sometimes used to supplement recycled water at a production of 100 AFY available to City supply (City of Santa Barbara Water Resources Division 2015). To maintain a sustainable yield from the groundwater basin, useable groundwater storage volume is approximately 16,000 AF (City of Santa Barbara 2020). Unit 1 and Foothill Basin recharge are both natural and artificial through injection via water production wells and diversions of Mission Tunnel water into Mission Creek for the purpose of promoting infiltration (City of Santa Barbara 2020). Groundwater management is important for the City as Storage Unit 1 is subject to saltwater intrusion.

With increased drought conditions, reliance on groundwater may continue to grow. This can become problematic as the implementation of the Sustainable Groundwater Management Act (SGMA) will enforce pumping restrictions to maintain the groundwater aquifer. Groundwater Sustainability Agencies (GSAs) will set a limit to the overall groundwater pumping activities by assigning capped portions to groundwater pumpers (Babbitt et al. 2018). SGMA requires GSAs to develop groundwater sustainability plans (GSPs) to maintain and preserve future groundwater levels. Groundwater sustainability is defined as the operation of the groundwater basin must not "cause undesirable results" which include depletion of groundwater and land subsidence (National Groundwater Association 2019). Groundwater management can be seriously impacted by climatic pressures: warming temperatures, shorter wet seasons, infrequent precipitation, and rising seas (Maven 2018).

Desalination

The Charles E. Meyer Desalination Plant was constructed in 1991 to help satisfy water demand during drought years. Due to adequate water supply, the plant was put in long-term storage mode

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[9] Groundwater basin recharge occurs when water infiltrates into the basin from precipitation or percolation through stream beds, irrigation, and artificial injection wells, saturating the aquifer in which it is stored (Rhode et al. 2014). The rate of recharge is dictated by the rate of water entering the system and the rate of infiltration, thus determining the amount of water lost due to evaporation (Thomas 2016).

[10] Overdraft occurs when the rate at which groundwater is being extracted exceeds the rate of groundwater basin recharge over an extended period of time (Moran et al. 2014).

(City of Santa Barbara 2020).[11] In 2015, the Santa Barbara City Council decided to re-commission the Charles E. Meyer Desalination Plant. The desalination plant is currently producing 3,125 AFY. The City currently holds a permit to expand the desalination plant to increase production up to 10,000 AFY (City of Santa Barbara 2019)

Expansion of the plant would allow the City to further supplement water needs during times of drought. The desalination process uses reverse osmosis membranes that are composed of synthetic organic polymers (Sagle & Freeman 2004). The reverse osmosis membranes act as a barrier to all dissolved salts, while allowing water to freely pass through the membrane. The rejection of dissolved salts is currently between 95 to 99%. Desalination currently satisfies 30% of the City water demand. However, desalination is costly and energy-intensive. The operating cost for the desalination plant is $4.1 million per year (City of Santa Barbara 2020).

Desalination requires 4,615 kilowatt hours (kWh) per AF of water, which decreased from 6,600 kWh per AF of water when the plant first operated (City of Santa Barbara Water Resources Division 2011). Overall, the reactivated plant uses 40% less energy than the original plant due to high-efficiency pumps and improved filter technology (City of Santa Barbara 2020). The 2011 LTWSP credits desalination as a vital resource and water supply back-up during droughts. According to the 2011 LTWSP, the operating price to produce one AF of water using desalination is $1,470 (City of Santa Barbara Water Resources Division 2011).

Recycled Water

The City currently has the capacity to treat and deliver 1,400 AFY of recycled water (City of Santa Barbara 2020). The current customer demand for recycled water is 800 AF (City of Santa Barbara 2020). The City began distributing recycled water in 1989 and in 2015 upgraded the El Estero Wastewater Treatment Facility to meet water quality standards[12] (Corey 2020). The primary use for recycled water is for landscape irrigation. The added benefit of using recycled water for irrigation is the higher nutrient concentration that the potable water supplies lack (City of Santa Barbara 2020). Recycled water is currently used at 50 different sites throughout the City (City of Santa Barbara 2020). The City is currently working on expanding the recycled water infrastructure to improve the resilience of the City water supply and meet the state mandate[13] on per capita water use (City of Santa Barbara Water Resources Division 2011).

Water management officials within California are switching to infrastructure that centers around recycled water, rather than constructing new dams and reservoirs. The California State legislature aims to increase recycled water use from 1 to 1.5 million AF by 2020 (Water Education Foundation

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[11] Charles E. Meyer Desalination Plant is offline (City of Santa Barbara - Public Works Department 2019).

[12] Before 2015 recycled water was supplemented with potable water to meet water quality requirements (Corey 2020).

[13] The state will require a limit for in-door water use per person to be set to 55 gallons per day in 2022 and 50 gallons per day by 2030 (Luna & Koseff 2018).

2019). Expanding potable water to take advantage of the existing water in the California distribution system can increase urban water supply by 40 percent (Pottinger 2016).

The pricing of recycled water makes it a desirable option, as the tiered recycled rates for southern California have a wholesale base rate of $449 per AF (Clumpner 2016). California uses 670,000 AF of recycled water annually, which represents 13% of the 5 million AF of wastewater produced annually (Pacific Institute & NRDC 2014). In 2003, the Recycled Water Task Force projected recycled water potential to range from 1.9 to 2.3 million AFY by 2030 (Pacific Institute & NRDC 2014). Coastal areas within California dump two-thirds of wastewater production into the ocean (Pacific Institute & NRDC 2014).

Water agencies throughout California have reported that recycled water production during drought years declined due to conservation efforts. Reduction of urban indoor water use decreased the quantity and quality of wastewater (McCann & Chappelle 2019). In a survey conducted by the Public Policy Institute of California in 2018 40% of wastewater agencies reported that their ability to produce recycled water was impaired due to the reduction of urban indoor water use (McCann & Chappelle 2019). As households become more water efficient, their discharge becomes saltier, affecting the quality of recycled water. The treatment process currently does not remove salts.

1.4 Sedimentation & Wildfire

Wildfire frequency and total acres burned across California are projected to increase due to predicted extended dry periods and hotter temperatures throughout the state (Westerling et al. 2011; Littell et al. 2009). Heightened sedimentation rates from post-fire ash deposition, newly exposed soils, and more intense rainfall events have direct impacts on the City’s water supply infrastructure and long-term storage.

Post-wildfire dynamics vary depending on the intensity of fire, duration, slope of the burned area, precipitation regime, and the impacts often last less than seven years (Moody et al. 2013). This recovery timeline varies based on vegetation regrowth, climate and precipitation variables, and basin morphology (Moody et al. 2013). Post-wildfire, topographically steep landscapes within an ecoprovince, such as Santa Barbara’s chaparral covered Santa Ynez Mountains, can be heavily influenced by rainfall intensity.

Factors affecting the potential for debris flows following wildfire events are evaluated by US Forest Service Burned Area Emergency Response (BAER) reports. These reports document the extent of soil burn severity, which degrades the existing surficial soil structure, affects organic material, and can form water repellent layers. After the Whittier Fire in July 2017, which burned about 18,000 acres in Santa Barbara County, the Forest Service compiled a BAER report to evaluate forest service lands affected by the fire (USDA Forest Service 2017). This report estimated the highest amount of sediment yield to occur during the first three years following the fire. After the fire, among soils with moderate to high burn severity, there was a notable removal of surficial organic and vegetative cover. Chaparral vegetative communities tend to have hydrophobic, or water repellant, soils and post wildfire processes tend to increase the hydrophobicity of soils (USDA Forest Service 2017). Removal of surficial vegetation and organic material coupled with increased soil hydrophobicity is likely to increase the rate of erosion, potentially increasing the probability of post-wildfire debris flows. Debris flows pose a multitude of consequences for surficial water sources, including increasing sediment inflow and decreasing water quality. In addition, the transport of sediment and nutrients post-wildfire may decrease dissolved oxygen concentrations in water bodies.

As rainfall has a large influence on sedimentation over post-wildfire regions, modeling has attempted to predict the likelihood of such extreme weather events temporally, and their associated debris flow impacts. These models have large uncertainty as post-fire runoff and erosion are not uniform and are often unpredictable (Moody et al. 2013). To determine the severity of a specific fire, several measurements are taken to understand impact, such as depth of the burn, which is a way of estimating total consumption of above-ground fuel. This measurement also indicates to what extent previously obstructed overland-flow is now more readily mobile (Moody et al. 2013). The USGS Landslide Program models the probability of post-wildfire debris flow and estimates the potential volume of flow following a rainfall event (USDA Forest Service 2017). The models used for this program require geospatial data including basin morphology, burn severity, and soil and rainfall characteristics.

Research on sediment yields within Santa Ynez Mountain watersheds has been conducted to assess the potential for quantitatively estimating future sediment yields following precipitation events. The rates and variation of suspended sediment discharge in Arroyo Burro, Mission Creek, Devereux Creek, and Gaviota Creek were examined to determine the relationship between sediment yield and discharge within this region (Warrick et al. 2015). Based on measurements taken from 2003 to 2006 among the four sub-watersheds, suspended sediment concentrations ranged over five orders of magnitude. Sediment yield may be related to peak discharge following intense precipitation events, but a strong relationship between these variables was not observed in each of the sub-watersheds. The wide range in suspended sediment discharge, along with the weak relationship between sediment yield and discharge, indicate that sedimentation is difficult to estimate and predict within the Santa Ynez watershed. This watershed is characterized by ephemeral discharge and highly variable precipitation events, which contributes to the variation in sediment yields throughout the area. Due to the variability in discharge, rainfall, and sediment yield, sediment models for the Santa Ynez watershed are unlikely to result in statistically significant estimations of sediment loads. However, it is important to qualitatively consider the potential impacts of sedimentation in the Santa Ynez watershed, as sedimentation following heavy precipitation events, specifically after recent wildfires, is likely to reduce the water storage capacities of Lake Cachuma and Gibraltar Reservoir.

As Lake Cachuma and the upstream Gibraltar Reservoir are integral parts of Santa Barbara's water supply infrastructure, loss in storage capacity must be considered in tandem with fluctuations in supply. In 2007, the Zaca Fire burned 60 percent of the Gibraltar Reservoir catchment. Since the fire and subsequent erosion, which was exacerbated by heavy rainfall winter of 2008, Gibraltar has lost over 1,500 AF of storage capacity as of 2010. Between 2007 and 2017, the Zaca, White, Rey, Whittier, and Thomas fires burned two-thirds of the greater Cachuma catchment. As the Gibraltar catchment is upstream from Cachuma, the smaller Gibraltar reservoir has been more vulnerable to sedimentation. Although Gibraltar has protected Cachuma's water capacity in this way, understanding when this buffer system might end is important. Sediment inflow has greatly reduced the water storage capacity of Gibraltar. In addition, Gibraltar reservoir is approaching the end of its estimated lifespan of 100 years. As a result of these impending issues, the City is evaluating the possibility of obtaining water from alternative sources to supplement the potential water storage lost from Gibraltar.

Reservoir sedimentation dynamics are not Santa Barbara specific. Worldwide reservoir storage loss due to sedimentation has now exceeded added storage capacity (Annandale 2006). The rate of reservoir sedimentation is largely determined by the water velocity, sediment composition and particulate size within a particular region (Annandale 2006). While sedimentation is a generalizable reservoir problem, Santa Barbara's steep topography, climate, and vegetation characteristics make its reservoirs especially susceptible to heavy sedimentation. Reservoir sedimentation not only reduces the reliability of water storage, but subsequently impacts overall drought tolerance.

1.5 Climate Change

Climate change is a result of anthropogenic greenhouse gas (GHG)[14] emissions which have increased since the pre-industrial era and are now larger than ever (IPCC 2014). The consequences of climate change have become more evident with extreme fluctuations in weather. On the global scale, the ocean and atmosphere are warming, ice and snow are decreasing, and sea level is rising (IPCC 2014). The intensity of future climate change impacts will depend on anthropogenic GHG emissions. Representative Concentration Pathways (RCPs) describe four different GHG emissions scenarios for the 21st century: a low emissions scenario (RCP 2.6), two intermediate scenarios (RCP 4.5 and RCP 6.0), and a high emissions scenario (RCP 8.5) (IPCC 2014). This report analyzes future climate change model projections under RCP 8.5 and an extended drought model to allow for water supply planning under the worst case scenarios.

Local Climate Change Impacts and Projections

Santa Barbara has experienced sea level rise, increasing air temperature, changes in precipitation, and increased wildfire intensity and frequency. The City assesses the local impacts of climate change and adaptation strategies on an ongoing basis, for example, through its Climate Action Plan and associated monitoring and reporting of the plan's implementation.

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[14] GHGs such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) trap heat in the atmosphere.

Sea Level Rise

Santa Barbara has already experienced some sea level rise and is projected to experience more by 2100 (City of Santa Barbara 2018). In planning for sea level rise, the City is considering the high emissions scenario (RCP 8.5) as well as the extreme risk scenario (H++) which accounts for the loss of the West Antarctic ice sheet (City of Santa Barbara 2018). These future sea-level rise scenarios project a rise of 0.8 feet in 2030, 2.5 feet in 2060, and 6.6 feet by 2100. Projected sea level rise could result in shoreline erosion, decreased beach widths, increased storm surges, and an abundance of coastal flood waters. Though some areas of Santa Barbara are more vulnerable to sea level rise than others, the impacts could be felt in the city through impacts to water infrastructure. The El Estero Wastewater Treatment Plant and the Charles E. Meyer Desalination Plant are expected to be impacted by increased flooding. Without preventive action, exposure of these facilities to tidal inundation[15] and flooding has the potential to leave the facilities inoperable by 2100 (City of Santa Barbara 2018).

Temperature, Precipitation, and Drought

Historical minimum and maximum temperature data were gathered for both Lake Cachuma and Gibraltar reservoirs from the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Information (NCEI). Average yearly maximum temperatures at Lake Cachuma and Gibraltar have been increasing over time (refer to Figures 9 and 10). Average minimum temperatures show an increasing trend in the early 1900s and a decreasing trend at Lake Cachuma since the late 1900s and 2000s. The decreasing trend in minimum temperature over the last 20 years at Lake Cachuma indicates cooler minimum temperatures over time, while average maximum temperatures at Gibraltar have been increasing since 1998, indicating warmer minimum temperatures (refer to Figures 11 and 12). Under RCP 8.5, Lake Cachuma[16] is projected to experience a nearly 4 degree Fahrenheit (°F) increase in maximum temperatures, and an increase of almost 5°F in minimum temperature by 2050, compared to 1990 observed temperatures. Under the same assumptions, Gibraltar Reservoir[17] is projected to experience a 5°F increase in maximum temperature and just over a 4°F increase by 2050 (Cal-Adapt).[18] By the end of the century, both Lake Cachuma and Gibraltar are projected to experience approximately 8°F increases in maximum temperatures and about 12°F increases in minimum temperature compared to 1990 observed temperatures (Cal-Adapt).

Historical precipitation data for Lake Cachuma and Gibraltar were obtained from Santa Barbara County Public Works Department. The historical precipitation trends at both reservoirs are highly variable (refer to Figures 13 and 14). Variability in yearly precipitation has expanded since the

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[15] Areas that are below non-storm high tide elevation once sea level rise is in effect.

[16] Grid Cell (34.59375, -119.90625).

[17] Grid Cell (34.53125, -119.65625).

[18] Averages are calculated over all 4 priority models described in the Climate Projections section: HadGEM2-ES (warm/dry), CNRM-CM5 (cool/wet), CanESM2 (average), and MicroC5 (complement).

1980s, indicating that dry spells and rainfall extremes have increased (City of Santa Barbara Planning Division 2018). In 2018, Santa Barbara received 54% of what is considered to be a normal amount of annual precipitation (City of Santa Barbara Planning Division 2018).

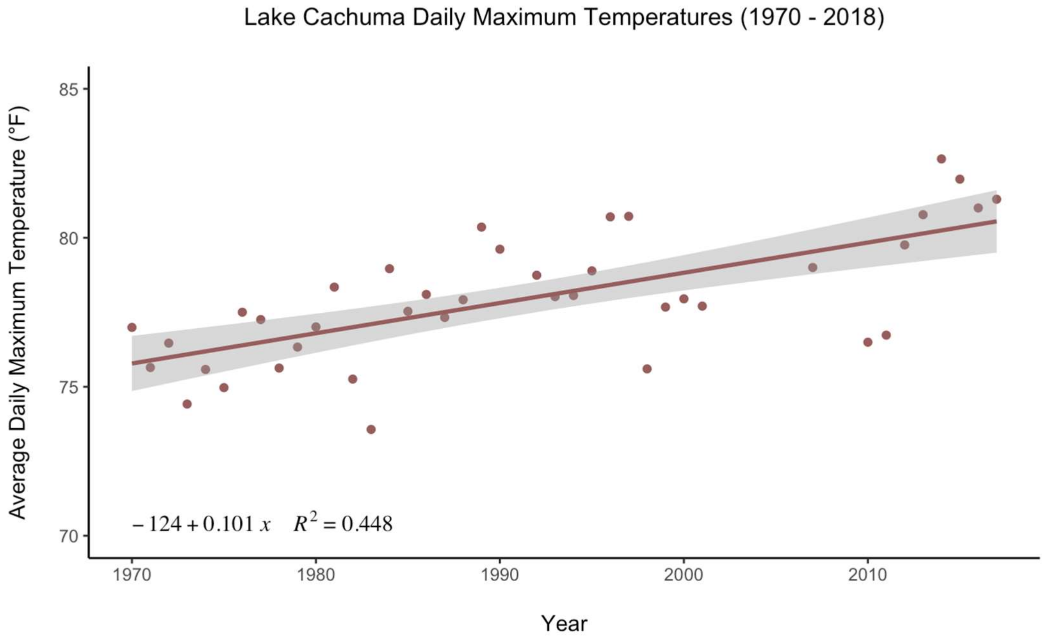

Figure 9: Average Maximum Yearly Temperature at Lake Cachuma. The linear regression is plotted with a 95% confidence interval. Data source: The National Center for Environmental Information (NOAA) Lake Cachuma Station. Accessed May 2019.

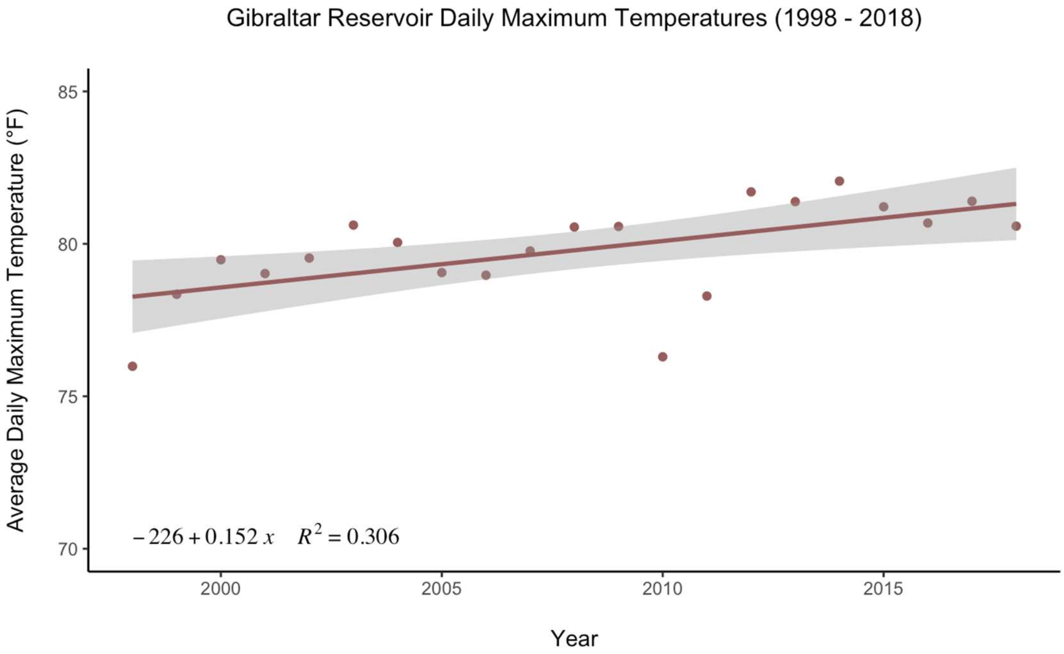

Figure 10: Average Maximum Yearly Temperature at Gibraltar. The linear regression is plotted with a 95% confidence interval. Data source: The National Center for Environmental Information (NOAA) Los Prietos Station. Accessed May 2019.

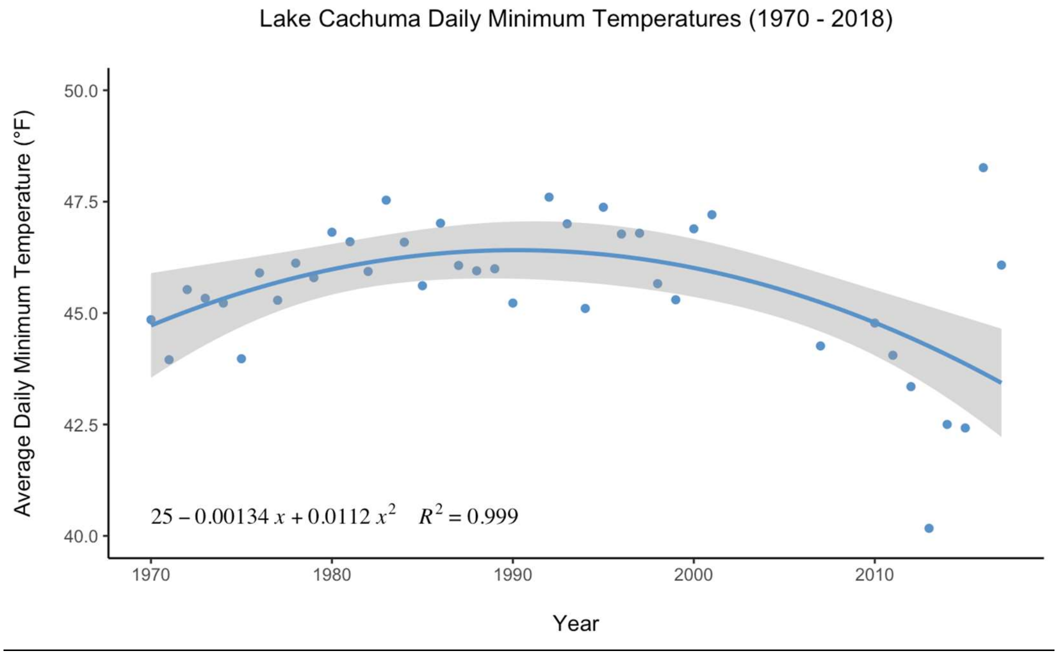

Figure 11: Average Minimum Yearly Temperature at Lake Cachuma. The quadratic regression is plotted with a 95% confidence interval. Data source: The National Center for Environmental Information (NOAA) Lake Cachuma Station. Accessed May 2019.

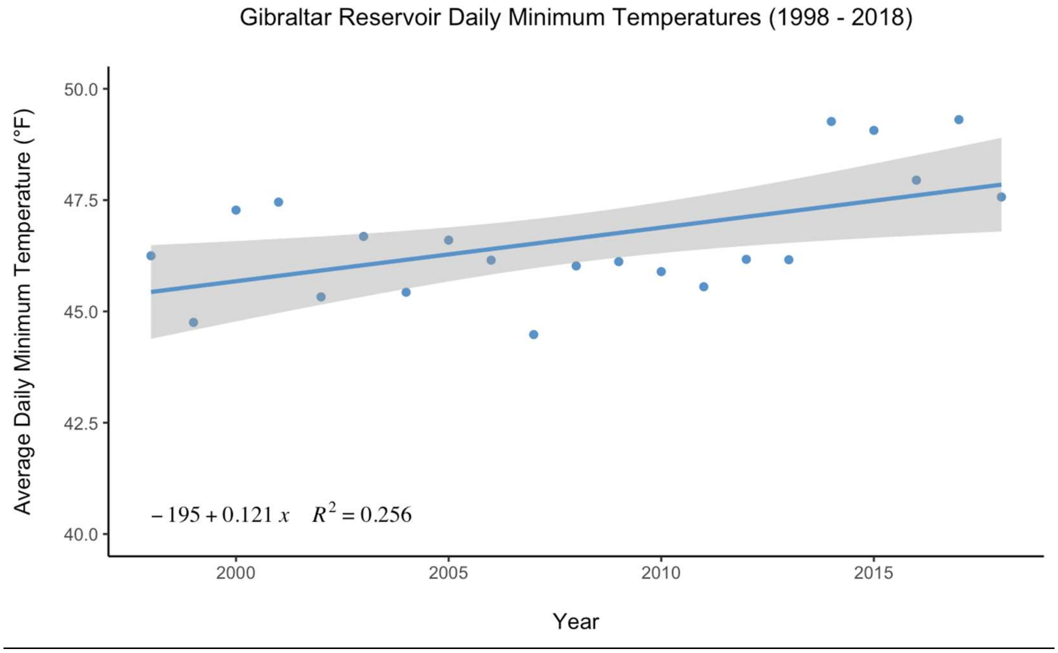

Figure 12: Average Minimum Yearly Temperature at Gibraltar. The linear regression is plotted with a 95% confidence interval. Data source: The National Center for Environmental Information (NOAA) Los Prietos Station. Accessed May 2019.

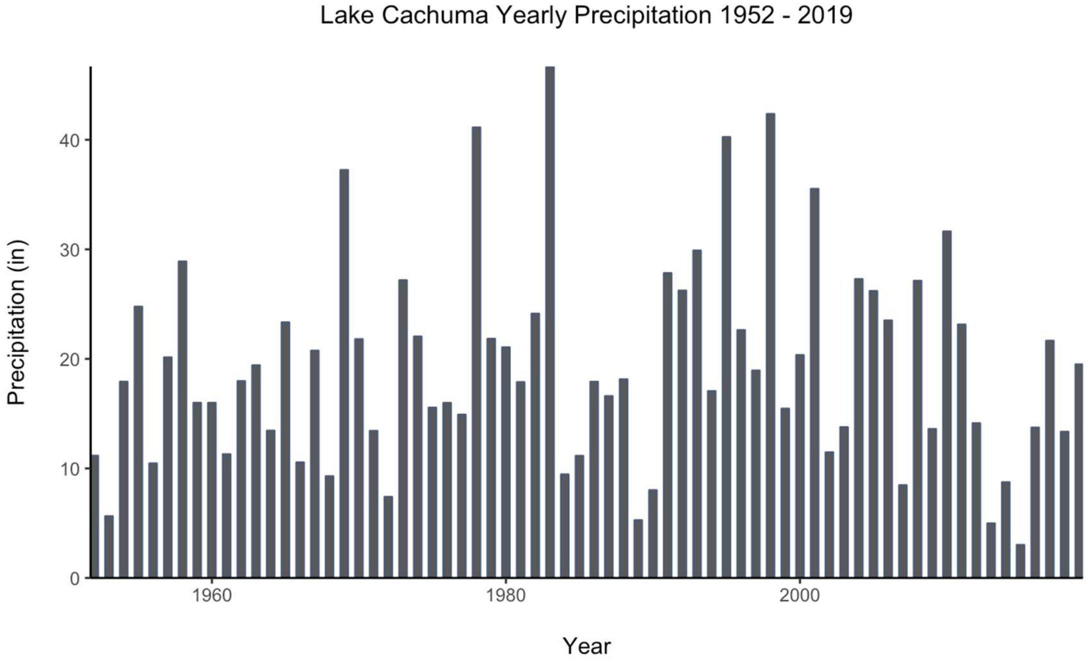

Figure 13: Total Yearly Precipitation at Lake Cachuma. Data source: Santa Barbara County, Public Works Department Cachuma Dam Station. Accessed May 2019.

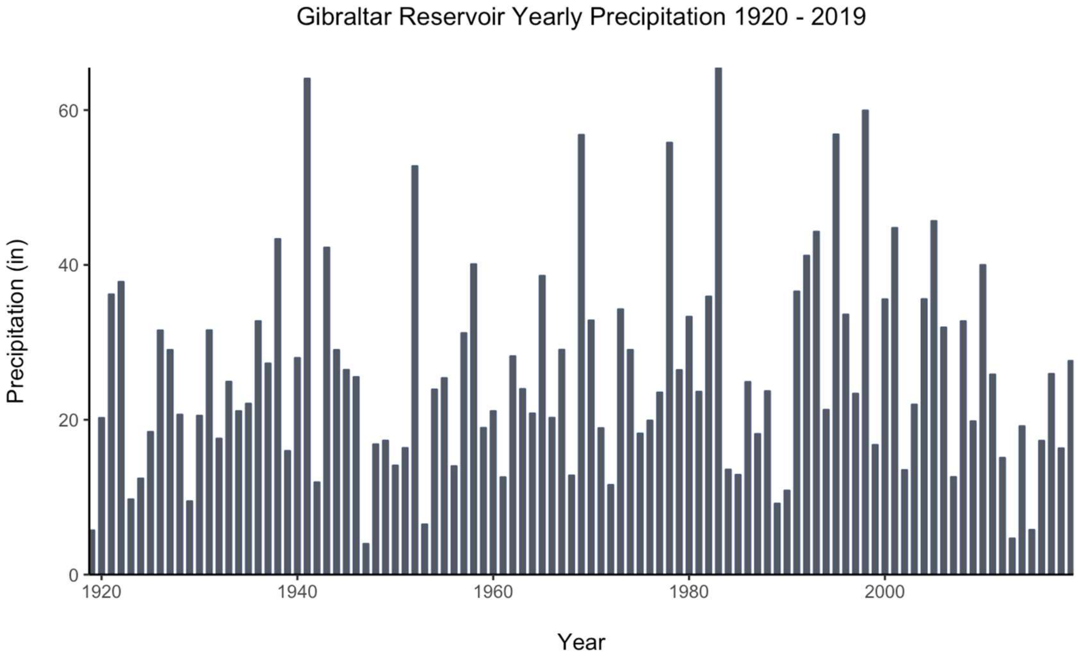

Figure 14. Total Yearly Precipitation at Gibraltar. Data source: Santa Barbara County, Public Works Department Gibraltar Dam Station. Accessed May 2019.

Wildfire

The chaparral-dominated Santa Ynez watershed is susceptible to infrequent, large, high-intensity fires (Figure 15). Since the early 1900s, fires have increased in intensity and frequency. The City expects that wildfire risk will increase due to projected climate changes (City of Santa Barbara 2012).

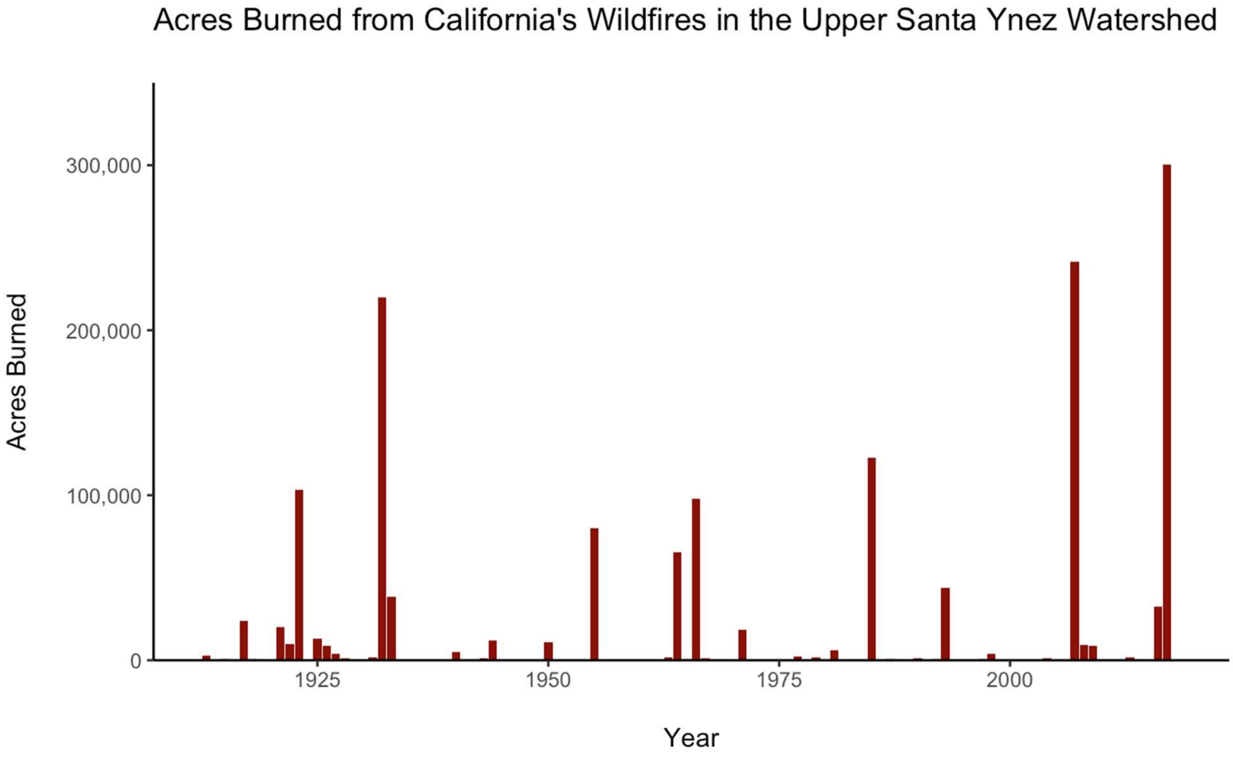

Figure 15. Acres burned in the upper Santa Ynez watershed. Data source: California Department of Forestry and Fire Protection's Fire and Resource Assessment Program. Accessed September 2019.

Climate Change Adaptation

The City's Climate Action Plan was enacted in 2012 to help prepare for and mitigate the potential impacts of climate change on the city. The Climate Action Plan focuses on reducing carbon emissions generated by the City, and adaptive strategies for climate change. The plan outlines a variety of adaptation planning strategies for fire, flooding, water quality, coastal vulnerability, public services, biological resources, and more. Adaptation approaches to climate change impacts on the water supply include the implementation of measures to increase water storage capacity and diversify water supplies, such as water sharing and banking agreements among jurisdictions.

Climate Change Models

In 2015, the California Department of Water Resources (DWR) released Perspectives and Guidance for Climate Change Analysis, which documents the selection of 10 GCMs based on criteria selected for water resources planning in California. Cal-Adapt uses these 10 models because they were deemed by DWR to be “the most suitable for California climate and water resource assessment and planning purposes” (DWR & CCTAG 2015). To provide a more manageable subset of models for researchers and practitioners to use, the Climate Action Team Research Working Group with the support and coordination of other groups selected four priority models that represent a range of possible futures for California. These four priority models as well as an extended drought scenario are used in the analysis. Projected future climate conditions from these five models are described as: (1) a *warm/dry* simulation (HadGEM2-ES); a *cool/wet* simulation (CNRM-CM5); an *average* simulation (CanESM2); a *complement* simulation (MIROC5); and an extended drought simulation. Of the 10 original models selected by DWR, the HadGEM2-ES *warm/dry* simulation was ranked the warmest across all seven metrics used to rank the models. These metrics encompass different annual and seasonal temperature and precipitation measures. The CNRM-CM5 *cool/wet* simulation was ranked the coldest of all the models. The CanESM2 *average* simulation was ranked average across these seven metrics and the MIROC5 *complement* simulation was ranked most unlike the other models. The *complement* simulation was selected to encompass a wide range of possibilities for the State. The extended drought simulation was derived from a dry spell simulated from the HadGEM2-ES *warm/dry* model and is applied to a 20 year period from 2023 to 2042 (Pierce & Daniel 2017).[19]

The climate projections have been downscaled from 32 GCMs at a 6-kilometer spatial resolution on a daily timescale from the Coupled Model Intercomparison Project Phase 5 (CMIP5) data archive (Cal-Adapt). The statistical technique used to downscale the climate projections is the Localized Constructed Analogs (LOCA) which estimates finer-scale detail using historical effects of topography on local weather patterns (Pierce & Daniel 2017).

1.6 Soil and Water Assessment Tool

Hydrological models are characterized as empirical, conceptual, or physical. Empirical models use mathematical equations based on the input data to make predictions about the watershed of interest (Devia et al. 2015). A conceptual model is based on reservoir storage, and uses a water balance equation that represents the hydrological cycle of the watershed (Sitterson et al. 2017). The water balance equation incorporates groundwater, evapotranspiration and runoff (Sitterson et al. 2017). A physical model or mechanistic model evaluates the characteristics of the watershed through physically[20] based equations and requires input data for the initial physical state of the watershed (Devia et al. 2015, Sitterson el al. 2017). A physical model incorporates spatial and temporal variability allowing the model parameters to better represent the physical characteristics of the watershed (Sitterson et al. 2017).

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[19] The simulated dry spell showed 78% of historical median annual precipitation.

[20] Physical base equations represent the real hydrologic responses within the watershed (Sitterson et al. 2017). A physical model.

The Soil and Water Assessment Tool (SWAT) is a widely used hydrological model. SWAT is a physically based model initially designed to simulate the impacts of agriculture and chemicals on the hydrological cycle in an ungauged basin. The development of SWAT spans over thirty years, originating with the Agricultural Research Service agency within the United States Department of Agriculture (USDA). SWAT has been cited in over 250 peer-reviewed articles and used to incorporate downscaled climate projections (Gassman et al. 2007). SWAT is used by different governmental agencies including the USDA and the U.S. Environmental Protection Agency (USEPA). SWAT is a versatile model that allows users to consider many environmental processes and adjust appropriate parameters involved within watershed hydrology. SWAT has an active community continuously improving the model. SWAT currently is compatible with ArcGIS (Version 10.5 and older) which allows the user to run the model through ArcGIS.

Chapter 2: Methodology

2.1 Data Description

To project climate change impacts on water supply, a firm understanding of the current state of water supply by examining local environmental and climate data was established. Historical data on environmental and climate factors including precipitation, temperature, evaporation, inflow, wildfires, and sedimentation were analyzed.

This study provides a quantitative assessment of the effect of climate change on Lake Cachuma and Gibraltar reservoirs, as they serve as the City's primary water sources. Groundwater, recycled water, and desalination were also examined because they are part of the City's water supply.

The project did not consider how climate change affects the City's water supply quality.

Data Sources

See Appendix 1 for a description of data sources.

Conceptual Model

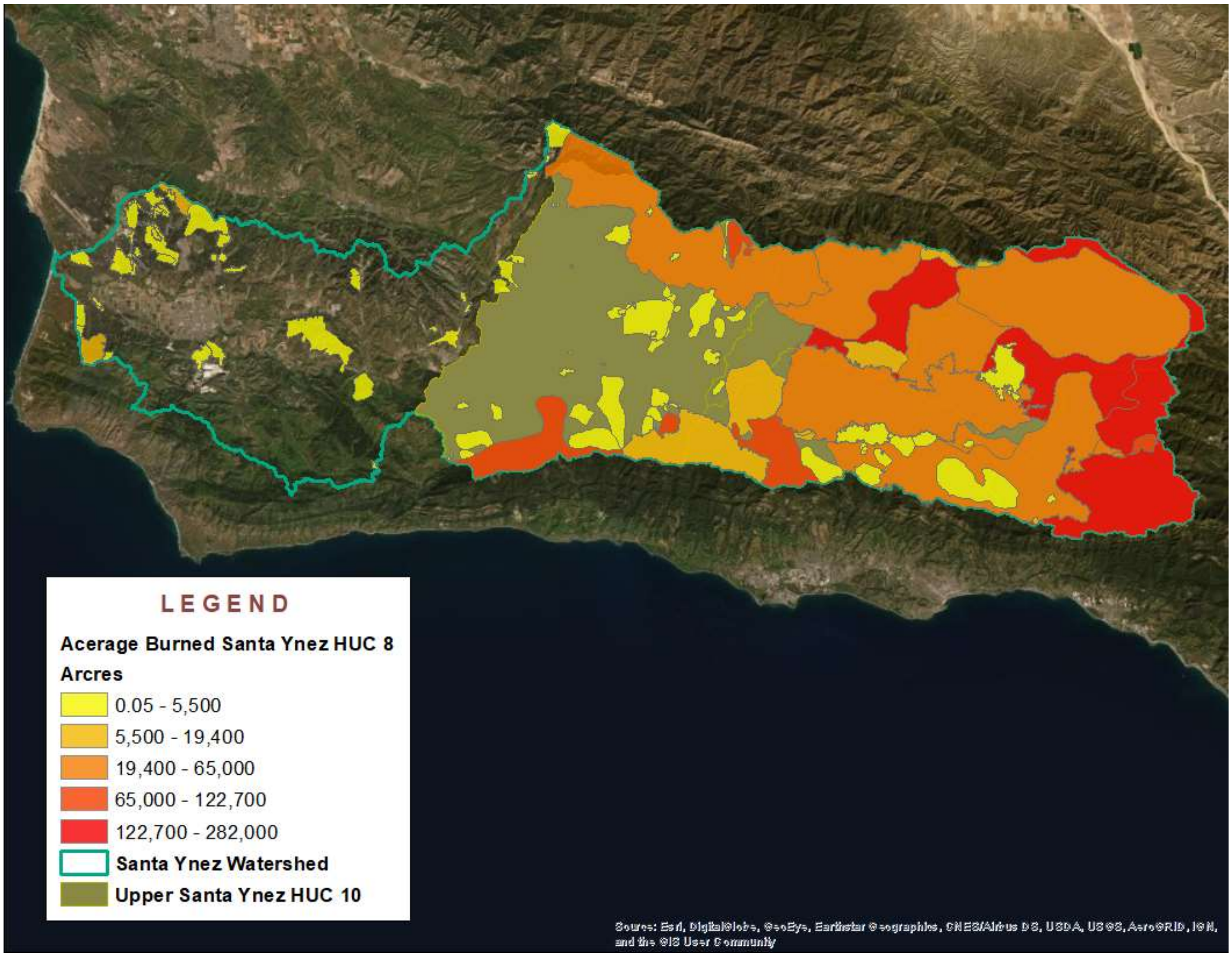
See Appendix 2 for a conceptual model of the data considerations and the relationship between climate change and different processes in the Santa Ynez River watershed.

City Water Supply and Demand Data

The City provided water supply data from 2005 to 2018 and per capita water usage data from 2010 to 2019. The City also provided projected yearly water demand to 2050.

Wildfire/Acreage Burned Data

Wildfire data were collected from CalFire Fire and Resource Assessment Program (FRAP). The data are for all recorded fires and acreage burned in California from 1913 to 2018. Acreage burned in the upper Santa Ynez watershed was delineated to encompass Alamo Pintado Creek, Santa Cruz Creek, Redrock Canyon, Mono Creek, and headwaters of the Santa Cruz River sub-watersheds in ArcMap GIS (Figure 16). This delineation was chosen rather than the entire SYR watershed as it includes only sub-watersheds surrounding or above Cachuma Reservoir, and therefore acreage burned that could directly impact Cachuma and Gibraltar reservoirs.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 16. Acreage burned in Santa Ynez watershed from 1913-2018. Data source: California Department of Forestry and Fire Protection's Fire and Resource Assessment Program. Accessed September 2019.

Reservoir Inflow

Lake Cachuma and Gibraltar reservoir levels are both tracked by "inflow" mass balances calculated by Cachuma Operations and Maintenance Board and City of Santa Barbara Public Works, respectively. These mass balance equations incorporate inflows, diversions, water overtopping the dams, and also precipitation and evaporation from the reservoirs. The equation below was used to normalize management parameters and only includes hydrologically relevant inflows into Lake Cachuma:

> ***Normalized Cachuma Monthly Total Storage*** *= Storage Volume – (Precipitation + Imported Water (CCWA)) + (Evaporation + Seepage + Managed Releases + Spills)*

The inflows and outflows accounted for in the mass balance are represented in the flowchart below, Figure 17, which also includes the USGS flow gauge of interest, Santa Cruz Creek.

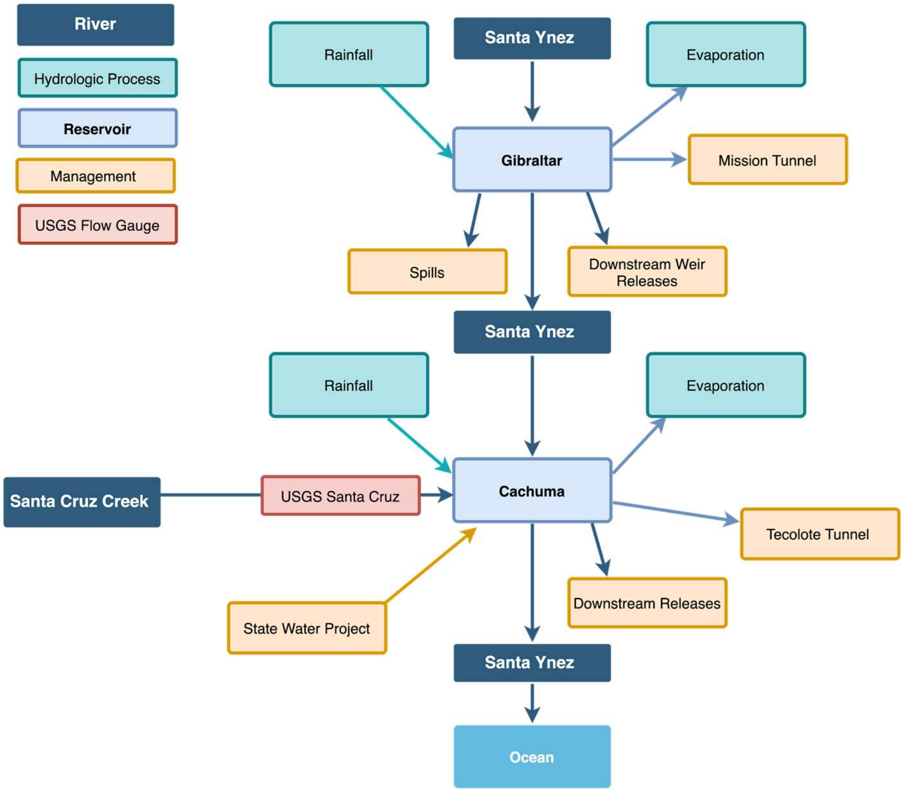


Figure 17. Schematic of Santa Ynez River watershed reservoir management. Based on the mass balance spreadsheets maintained for Gibraltar and Cachuma reservoirs. This chart also includes USGS flow gauge, Santa Cruz Creek.

While mass balances are helpful in characterizing reservoir levels for management purposes, both reservoir inflow datasets are simplified. To estimate how the entirety of the upper SYR watershed contributes to reservoir inflows, the relationship between monthly changes to the reservoir mass balances and historical streamflow was evaluated. Specifically, the relationship between Cachuma Reservoir inflows and the upper Santa Ynez hydrology was established through analysis of USGS Santa Cruz Creek discharge data. The Cachuma mass balance was focused on because Santa Cruz Creek flows directly into Cachuma and its historical discharge data was used to calibrate the ArcSWAT model.

USGS average daily flow data from January 1, 1983 to November 20, 2018 was downloaded from two gauges: 11123500 (SYR below Los Laureles Canyon and just upstream of Cachuma Reservoir) and 11124500 (Santa Cruz Creek, a tributary that discharges directly into Cachuma reservoir) (Figure 18). Flow gauges closer to Gibraltar Reservoir were immediately below the dam, and therefore cannot be used to characterize streamflow in the upper SYR Basin. While the USGS Los Laureles flow gauge partially represents hydrology in the upper SYR, it is also controlled by Gibraltar Reservoir management. The Los Laureles gauge is also influenced by the adjacent and large groundwater well which impacts surface discharge and therefore was not used for model calibration. The USGS Santa Cruz discharge, which is not influenced by an upstream reservoir and is monitored regularly by USGS, is therefore relied upon for model calibration.

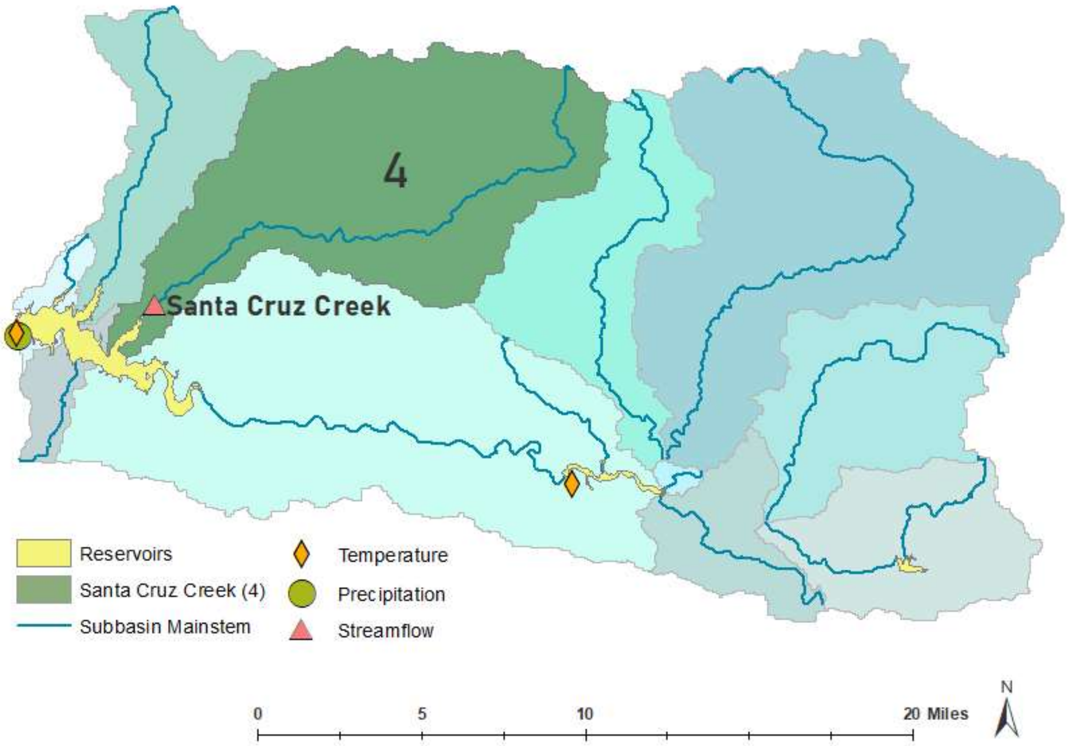


Figure 18: Precipitation, flow, and temperature stations within the upper Santa Ynez watershed. The precipitation gauges are monitored by the County of Santa Barbara, the flow gauges belong to the USGS, and the temperature stations are maintained by the National Oceanic and Atmospheric Administration (NOAA).

Climate Projection Data

Projected minimum temperature, maximum temperature, and precipitation data for both Gibraltar Reservoir and Lake Cachuma were obtained from Cal-Adapt. Cal-Adapt is a web-based climate adaptation planning tool designed to offer insight into how climate change might affect California at the local level (6-kilometer resolution). It synthesizes 10 downscaled[21] climate change scenarios and climate impact research in an interactive platform. The high-emissions scenario (RCP 8.5), in which greenhouse gas emissions continue to rise over the 21st century before leveling off, was used. This scenario was deemed the most conservative scenario by the City.

Four priority models, that represent a range of possible futures for California as well as an extended drought model, were used. The five models are described as:

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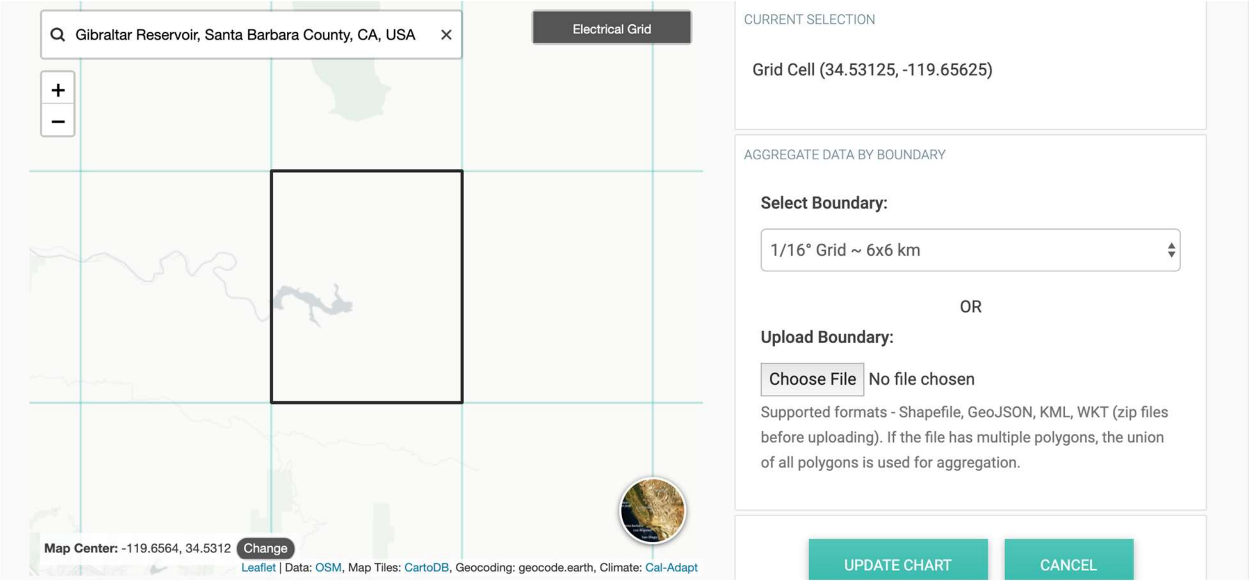
[21] Climate projections have been statistically downscaled using the Localized Constructed Analogs (LOCA) technique.

- A *warm/dry* simulation (HadGEM2-ES)
- A *cool/wet* simulation (CNRM-CM5)
- An *average* simulation (CanESM2)
- A *complement* simulation (MIROC5) - the model simulation that is most unlike the first three for the best coverage of different possibilities
- An extended drought simulation - early century dry spell from 2023 to 2042 identified from the HadGEM2-ES simulation

The delta change method was used to statistically downscale the five GCMs to a more useful scale for ArcSWAT modeling (Appendix 3). Percent changes in maximum temperature, minimum temperature, and precipitation were calculated for the following time periods: 2020s, 2030s, 2040s and 2050-2100 (Appendix 4).[22] This method was used to project temperature changes at Lake Cachuma and Gibraltar Reservoir and precipitation changes at Lake Cachuma. The projected decadal changes in precipitation and temperature were then applied to the historical climatic data, resulting in new projected temperature and precipitation files that were then used to simulate projected future streamflow. Streamflow was simulated for each of the five climate models.

Figures 19 and 20 show the 6x6 kilometer grid cells used to obtain climate projections for Lake Cachuma and Gibraltar Reservoir. For each, maximum and minimum temperature projections were obtained.



Gibraltar Reservoir, Santa Barbara County, CA, USA

CURRENT SELECTION

Grid Cell (34.53125, -119.65625)

AGGREGATE DATA BY BOUNDARY

Select Boundary: 1/16° Grid ~ 6x6 km

OR

Upload Boundary: No file chosen

Supported formats - Shapefile, GeoJSON, KML, WKT (zip files before uploading). If the file has multiple polygons, the union of all polygons is used for aggregation.

Map Center: -119.6564, 34.5312

Leaflet | Data: OSM, Map Tiles: CartoDB, Geocoding: geocode.earth, Climate: Cal-Adapt

Figure 19. Cal Adapt 6X6 kilometer grid cell for Gibraltar Reservoir.

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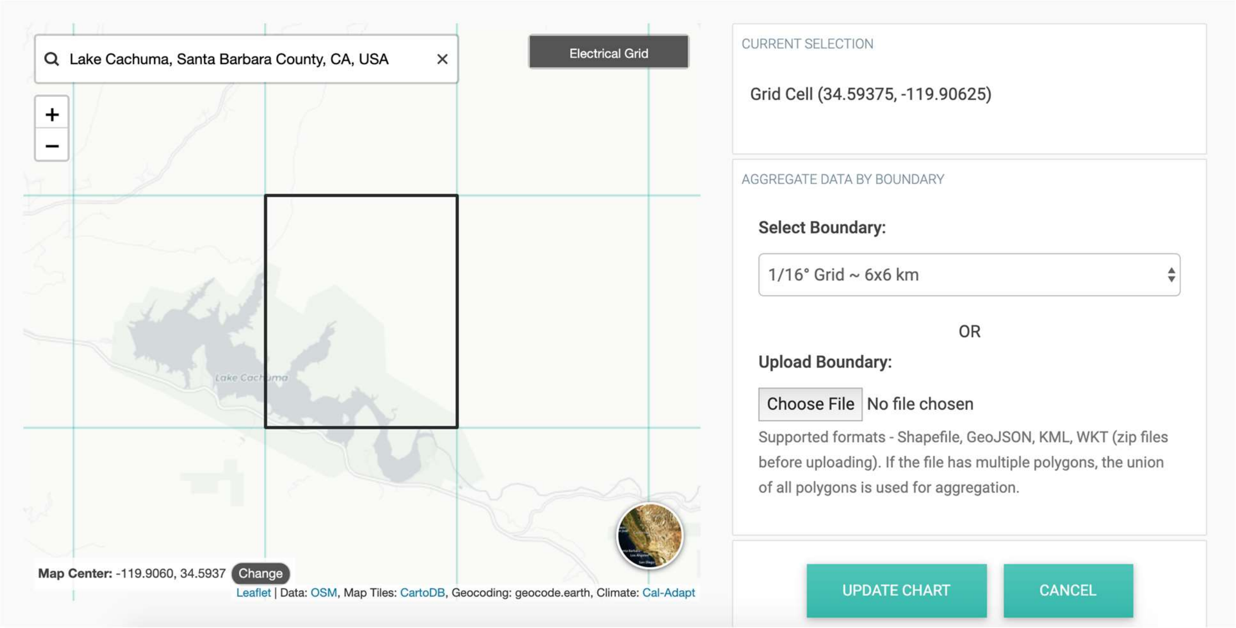
[22] Percent change calculated for each time period compared to historical observations (for each climate model).



Lake Cachuma, Santa Barbara County, CA, USA

CURRENT SELECTION

Grid Cell (34.59375, -119.90625)

AGGREGATE DATA BY BOUNDARY

Select Boundary: 1/16° Grid ~ 6x6 km

OR

Upload Boundary: Choose File No file chosen

Supported formats - Shapefile, GeoJSON, KML, WKT (zip files before uploading). If the file has multiple polygons, the union of all polygons is used for aggregation.

Map Center: -119.9060, 34.5937

Figure 20. Cal Adapt 6X6 kilometer grid cell for Lake Cachuma.

Reservoir Volume

Monthly water storage data for Gibraltar and Cachuma were obtained from the County of Santa Barbara (Figures 21 and 22). Cachuma's data extends from 1955 to 2019, whereas Gibraltar's volumetric data ranges from 2001 to 2019. Gauges record the capacity of each reservoir on a daily basis. The County averaged the daily recordings, providing monthly capacity values, or total volume of water stored.

Water Storage

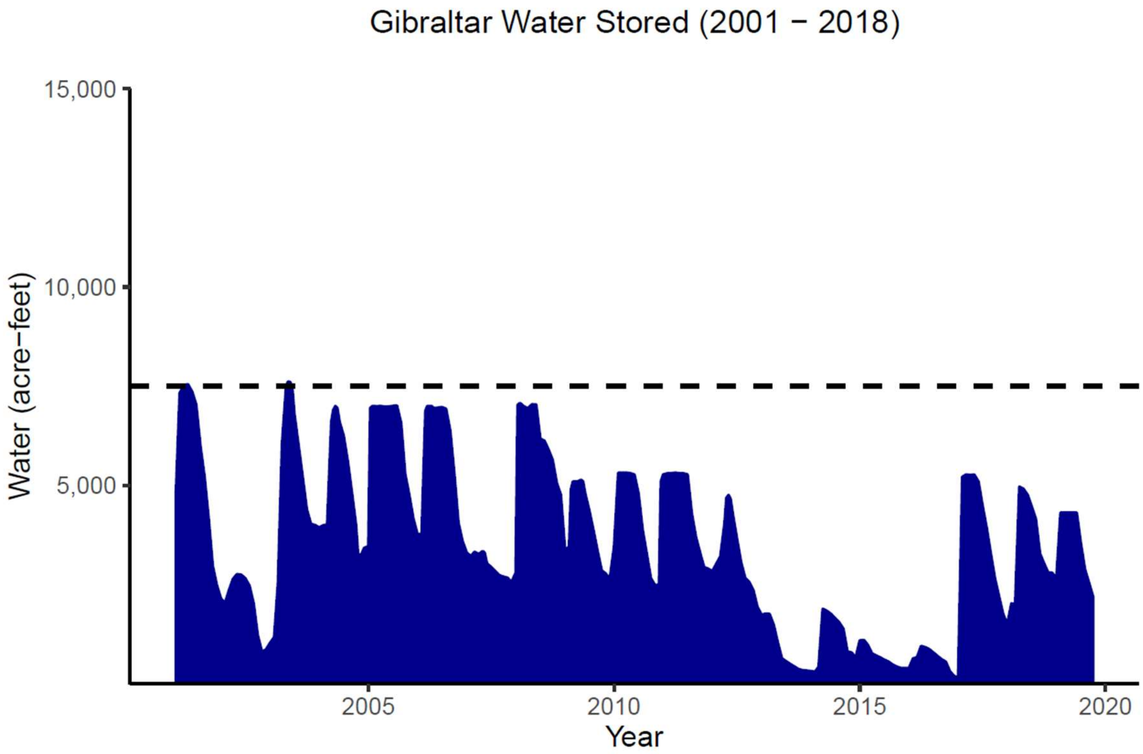


Figure 21: Historical Water Storage for Gibraltar 2001 - 2018. Source: Santa Barbara County, Public Works Department.

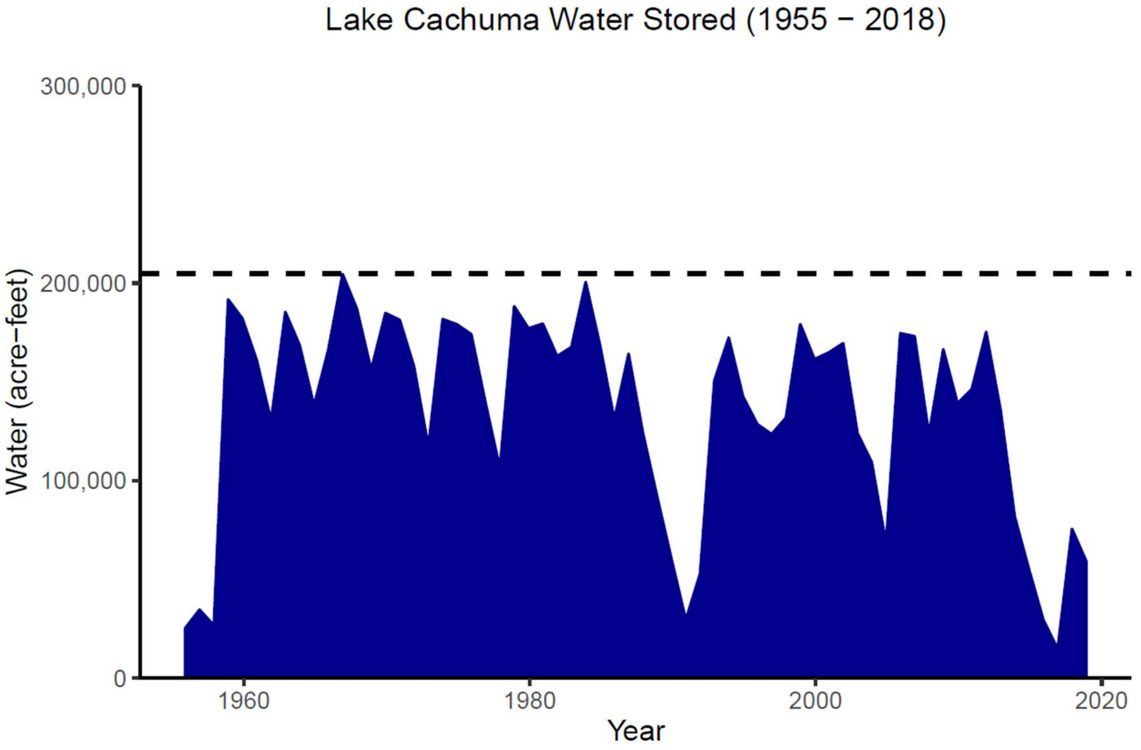


Figure 22. Historical Water Storage for Cachuma 1955 - 2018. Source: Santa Barbara County, Public Works

Department.

Reservoir Sedimentation

Data from the County of Santa Barbara, Cachuma Operations and Maintenance Board, and the City were used to gain an understanding of historical reservoir sedimentation.

Capacity Data

Utilizing bathymetric surveys for Gibraltar from the City and monthly water storage data for Cachuma from the County of Santa Barbara, reservoir sedimentation was derived. The maximum reservoir capacity, or total volume available for water storage, for Gibraltar was determined by the most recent bathymetric survey to create a cross section of historical reservoir capacity (Figure 23). These surveys indicate how full the reservoir is with sediment, and therefore by what volume the total reservoir capacity has decreased. For Cachuma, changes in water storage capacity from year to year were associated with sediment influx to create a cross section of historical reservoir capacity (Figure 24).

Prior to 2019, bathymetric surveys of Gibraltar were obtained using a “single-beam” approach in which cross-sections were collected throughout the reservoir at intervals of 300 feet. Beginning in 2019, the contractor conducted a bathymetric survey using a “multibeam” approach, which collects more data points than the single-beam method. The multibeam method is considered to provide a more accurate bathymetric assessment because it can better assess areas closer to the shoreline. It is important to note that bathymetric surveys conducted using different methods cannot be easily compared because the single-beam method can yield a different capacity result in comparison to the multibeam approach. In 2019, separate bathymetric surveys of Gibraltar were conducted using the single-beam and multibeam methods, respectively.

In 1948, Gibraltar Dam was raised to increase its volumetric capacity. To account for this increase in capacity, 14,500 AF is used as the maximum capacity for the years 1920 and 1944 and 14,800 AF is used as the new capacity after 1948 to calculate the sediment influx for the remaining years.

The difference between the original reservoir capacity and the maximum total storage capacity, calculated monthly, is used to determine the sediment influx for the Cachuma Reservoir. The difference between the original maximum storage capacity of the reservoir and the total water capacity within a specific month should be attributed to siltation. For example, the difference between the original maximum water capacity for Cachuma and total water capacity for October 1955 is 0 AF. This makes sense, as the reservoir was constructed in 1953, so it is expected that little sediment inflow has occurred in two years. However, the difference between the original maximum water capacity and total water capacity for May 2009 is ~9,296 AF. This value is expected, as siltation over a period of 56 years should decrease Cachuma’s water capacity substantially (Figure 11).

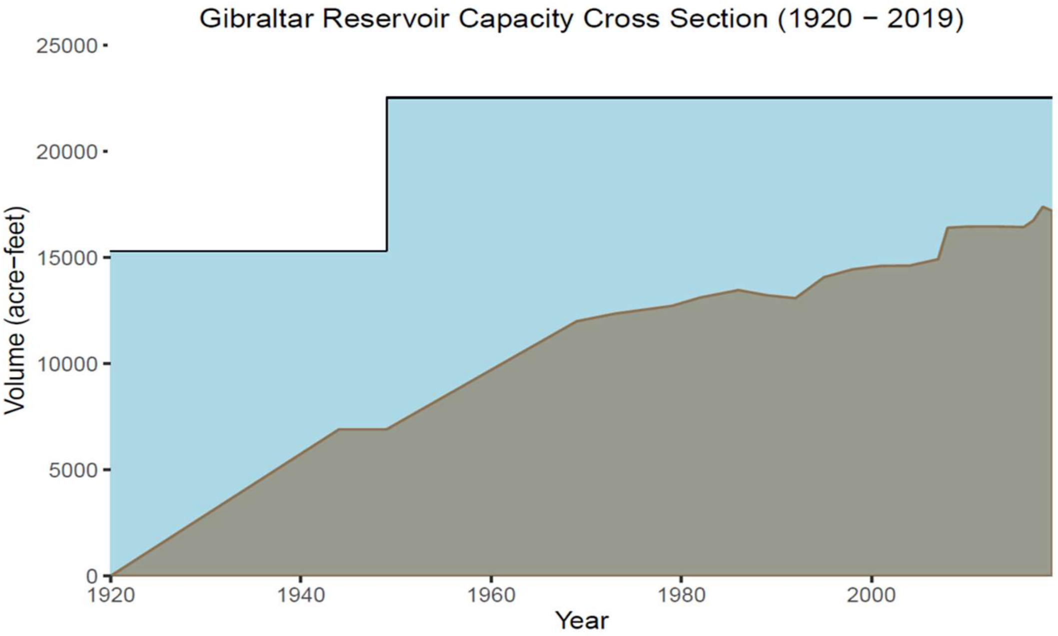


Figure 23. Reservoir Capacity of Gibraltar 1920 - 2019. The tan area indicates sediment accumulation within the reservoir, whereas the blue area indicates available water capacity. The solid black line represents the total capacity of the reservoir, including sedimentation. In 1949, the dam was raised, increasing the capacity of Gibraltar Reservoir. Data source: City of Santa Barbara, Public Works Department.

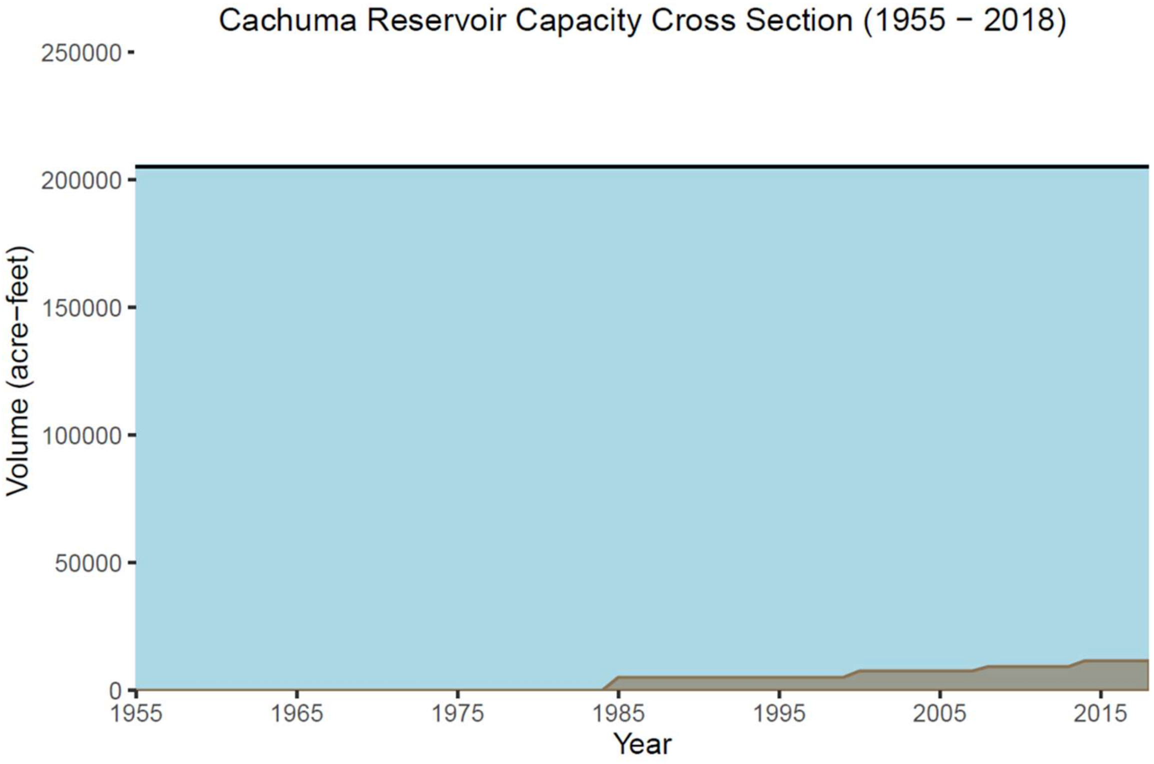


Figure 24. Reservoir Capacity of Cachuma 1955 - 2018. The tan area indicates sediment accumulation within the reservoir, whereas the blue area indicates available water capacity. The solid black line represents the constructed total capacity of the reservoir, 205,000 AF. Current water storage availability is ~193,000 AF. Data source: County of Santa Barbara.

Sedimentation, Precipitation, and Wildfire Exploration

Since chaparral is the predominant vegetation type in the Santa Ynez watershed, it is especially susceptible to infrequent, large, high-intensity fires. Fires result in a decrease in vegetation and infiltration rates due to ash, increasing erosion, and runoff. These conditions increase the likelihood of landslides and debris flows, which increase sediment supply. Figure 25 below illustrates acres burned, sedimentation (using reservoir capacity as a proxy), and precipitation at Gibraltar Reservoir from 1913 to 2018. Reservoir capacity decreases after the two largest fires that occured in the last 20 years. This could indicate increased sedimentation of the reservoir due to the acres burned in the reservoir and potentially large precipitation events following those fires.

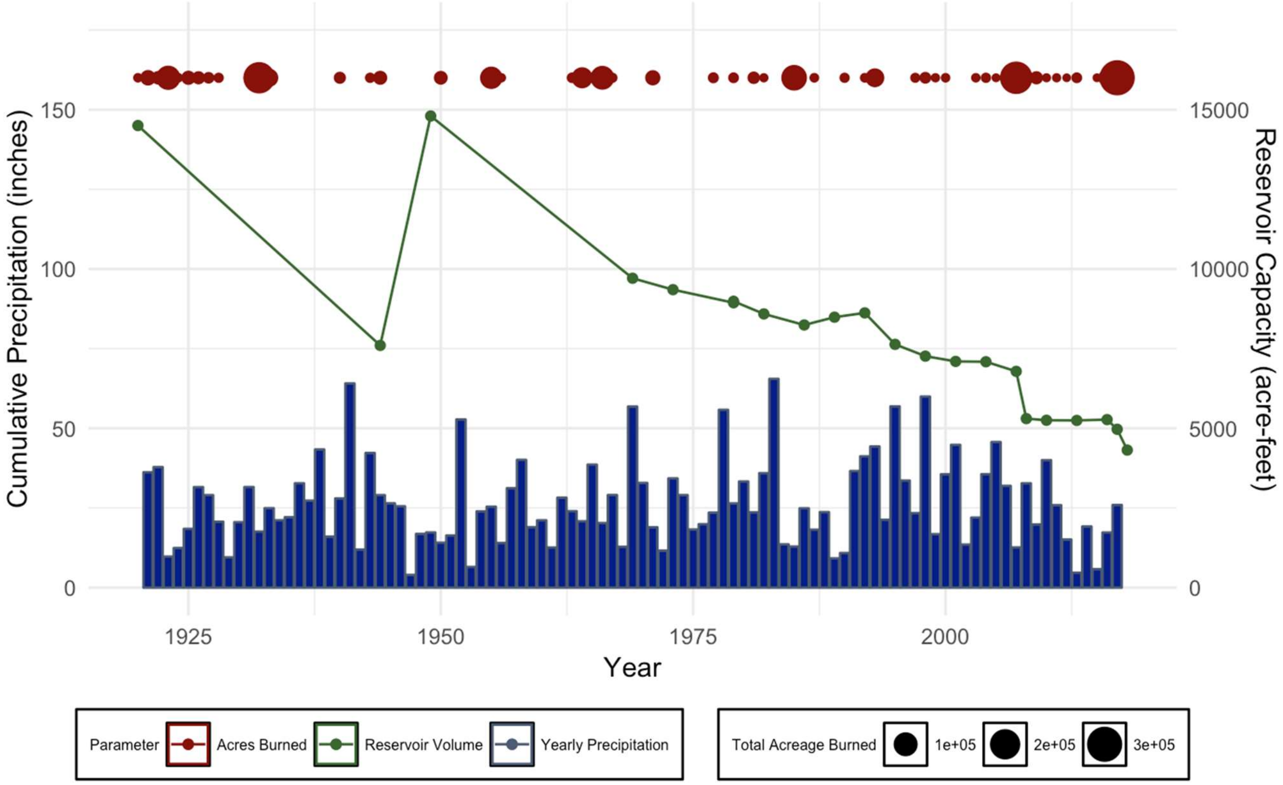


Figure 25. Acreage Burned, Sedimentation, and Yearly Precipitation at Gibraltar 1913 - 2018. Fire data source: California Department of Forestry and Fire Protection's Fire and Resource Assessment Program. Accessed September 2019. Reservoir capacity source: City of Santa Barbara, Public Works Department. Precipitation data source: Santa Barbara County, Public Works Department Gibraltar Dam Station. Accessed May 2019.

2.2 Hydrologic and Climate Modeling

Hydrologic models are useful tools in water resource management particularly in assessing the impacts of land use and climate change on water resources. Several hydrologic models were considered, including RiverWare and Santa Ynez River Hydrologic Model. RiverWare could not be used due to proprietary issues and the Santa Ynez River Hydrologic Model was not used because it is outdated.

Soil and Water Assessment Tool (SWAT)

The SWAT model is a physically based model designed to test and predict water and sediment circulation and agricultural production in ungauged basins (Devia 2015). The Soil and Water Assessment Tool (SWAT) is a highly regarded model that has been used extensively to study the impact of climate change on the hydrological cycle of the watershed. SWAT has been used in over 250 peer-reviewed published articles, and has been employed by numerous government agencies[23] (Gassman et al. 2007). The SWAT model, used through the spatial database (ArcSWAT), has been successfully used to simulate flows, sediment, and nutrient loading of a watershed (Narsimlu 2015). To accurately predict the movement of pesticides, sediments, and nutrients SWAT must be able to accurately model the hydrological cycle of the watershed (Neitsch et al. 2011). SWAT utilizes a water balance equation, to accurately simulate the conditions of the hydrologic cycle (Neitsch et al. 2011). For an in depth explanation of the water balance equation SWAT utilizes refer to Appendix 5.

Model outputs were assessed using R (version 3.0.1+) a statistical analysis software with the workspace management interface RStudio. Given that both data sets had daily values for precipitation, the average of the daily values was used to obtain total precipitation for a given year. Having a visual representation of the model outputs and historical data showed how well the peaks (high values) and valleys (low values) were aligned. The alignment of the peaks and valleys showed the accuracy of the model outputs generated from the SWAT simulation. Higher accuracy was anticipated from SWAT due to incorporating precipitation data from the City into the model versus using weather data from the model database. The process of adjusting model parameters (Figure 26) allowed for more accurate model outputs from SWAT simulations. Establishing model accuracy is essential, for the SWAT simulations incorporating climate models from Cal-Adapt to project future precipitation values for Lake Cachuma.

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[23] SWAT has been used by the USDA to support the Conservation Effects Assessment Project, which quantifies the environmental benefits of conservation at the national and watershed scale. SWAT also has been used by the European Commission to assess the impacts of climate change for five different watersheds across Europe for the Climate Hydrochemistry and Economics of Surface-water Systems project (Gassman et al. 2007).

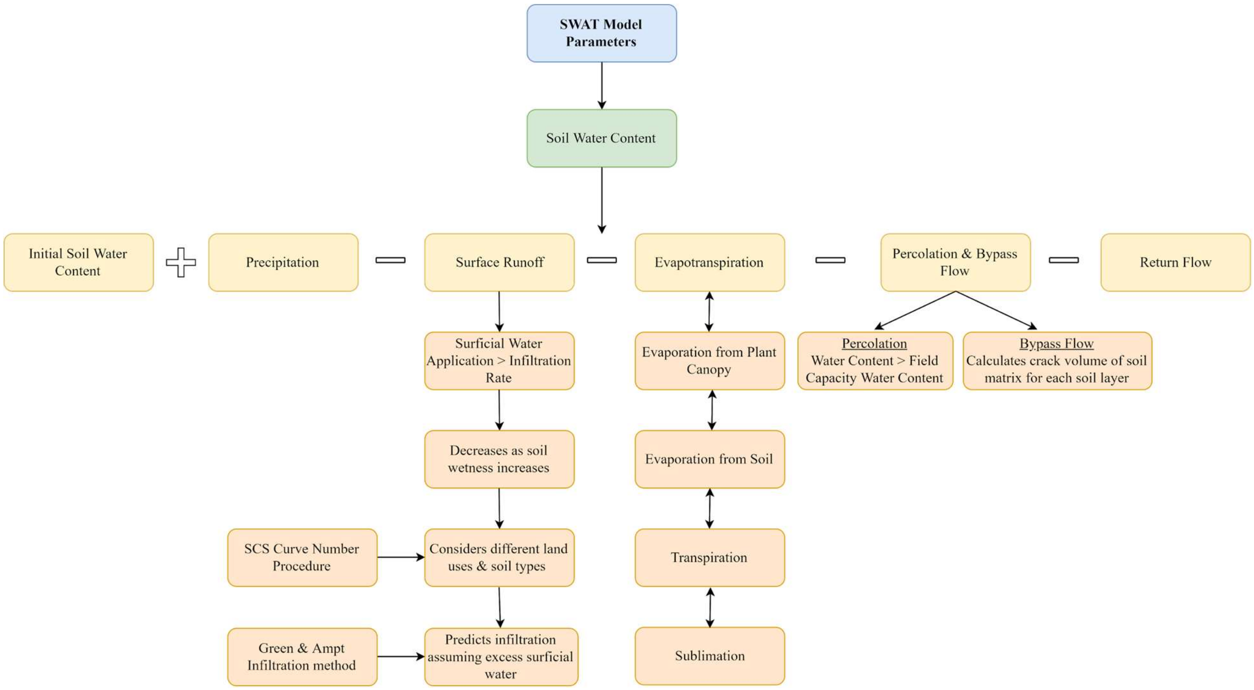

Figure 26: Schematic of SWAT Model Parameters. Hydrologic SWAT model parameters relevant to the project are included in this schematic. Groundwater, water quality, and vegetative coverage parameters are not quantitatively considered by this project.

Input Data

ArcSWAT, an ArcGIS extension tool, was used to build a model to delineate the Santa Ynez watershed and to define the sub-basin boundaries. The process of watershed delineation begins with the input of spatial data (Table 1). Sub-basins were delineated using grid cell boundaries by inputting a 100-meter resolution digital elevation model (DEM) file into ArcSWAT, which were acquired from BASINS (Version 4.5). BASINS allows users to access environmental databases to acquire watershed data (EPA 2019). A DEM raster was downloaded from BASINS to provide topography in meters (Amatulli et al. 2018). Following the input of the DEM raster, the critical stream area threshold was created to map and define the stream network. Establishing the stream network allowed ArcSWAT to define inlets and outlets which show where streams enter and exit the region (Briley 2010).

The sub-basins were further divided into hydrologic response units (HRUs) based on the land use and soil type of the sub-basin. ArcSWAT establishes a variety of loadings for each HRU that includes water and sediments (Zhang 2015). A land use shp file received from the National Land Cover Database (NLCD) was uploaded from USGS. The NLCD 2001/2006 classification lookup table was used to specify the land cover to be modeled (Winchell et al. 2013). The Digital General Soil Map of the United States (STATSGO2) was accessed through the ArcSWAT database. STATSGO2 is soil data collected through the National Cooperative Soil Survey and is designed for broad planning and land management at the regional level (USDA).

The slope was adjusted within the ArcSWAT interface. The slope offers information about the topography of the watershed, by estimating how precipitation influences runoff (Chapter 2 Watershed Characteristics). The slope was classified in groups from 0, 10, 20, 30, and 40. The HRUs were defined by adjusting the threshold for land, soil, and slope: land use percentage (1%), soil class percentage (2%), and slope class percentage (0%). This slightly simplified the way ArcSWAT delineates differences in the hydrologic conditions for each sub-basin. Defining HRUs allows SWAT to calculate runoff for each HRU separately.

Table 1: Spatial Data Utilized by SWAT.

Spatial Data	Description	Source
Digital Elevation Model (DEM)	Display drainage and flow within the watershed	Accessed through Basins 4.5; USGS National Elevation Dataset
Land use shape file	Provides spatial reference and illustrative data for land surface	Accessed through Basins 4.5; USGS Land Cover National Database
STATSGO2 Database for California	Description of soil types and distribution throughout the watershed	Accessed through ArcSWAT database; National Cooperative Soil Survey
Hydrology	Provides stream networks and catchments in the watershed	National Hydrology Dataset Plus v2.1

SWAT Simulation

The SWAT simulation ran from 1/1/1980 to 12/31/18 as the data from the County of Santa Barbara was not complete through 2019. Table 2 shows the location and elevation of gauges of the recorded data utilized for the SWAT simulation. Figure 27 shows the overall process of creating a ArcSWAT project and running the SWAT simulation. A detailed account of setting up the ArcSWAT project can be seen in Appendix 6.

Table 2: Locations & Elevations of Gauges. Data recorded by these gauges were inputted into SWAT. These gauges are monitored by the County of Santa Barbara.

Location	Latitude	Longitude	Elevation
Lake Cachuma (Station 332-subbasin 2)	34-34-52	119-58-47	800 Feet
Gibraltar Reservoir (Station 230 - subbasin 7)	34-31-21	119-40-56	1500 Feet

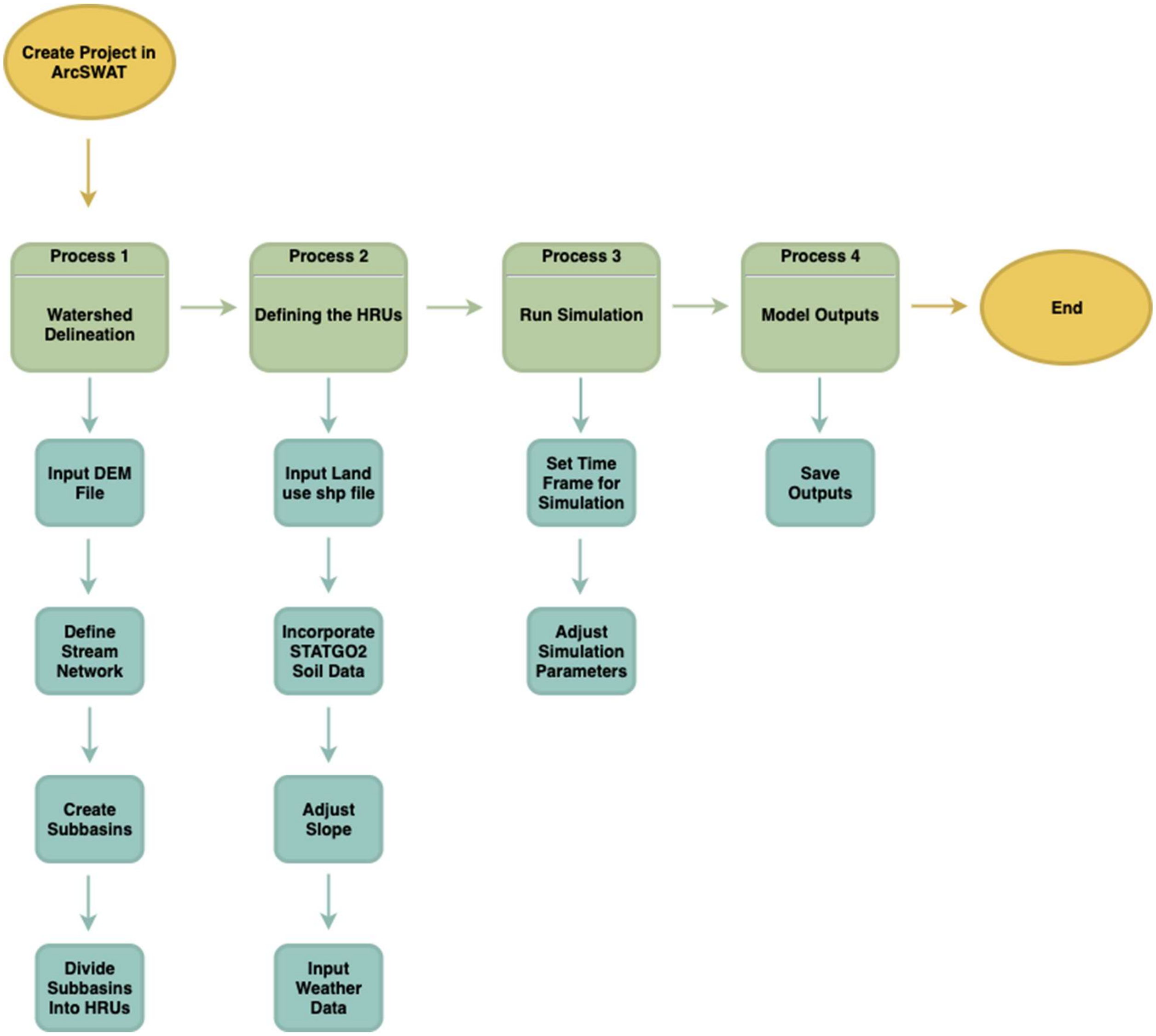

Figure 27. ArcSWAT Calibration Flow Chart.

Chapter 3. Results

After synthesizing historical data on the City's water supply sources, local weather conditions, SYR watershed physical characteristics, and Cal-Adapt precipitation and temperature projections, the hydrologic SWAT model simulated streamflow for the historical time period of 1980 to 2018. After obtaining simulated streamflow and comparing these values to historical observed streamflow, it was determined that the SWAT model required calibration via parameter adjustment.

Once the model was calibrated to a sufficient level, based on statistical comparisons between historical observed and model simulated streamflow, Cal-Adapt daily temperature and precipitation data from five climate models for the time period of 2020 to 2058 were put into the SWAT model. Running the model with these climate forcings produced projected streamflow for each climate model. Lastly, using the historical relationship between inflow from Santa Cruz Creek into Lake Cachuma, the projected streamflow from the sub-basin associated with Santa Cruz Creek was translated into a basin-wide estimate of the volume of water entering Lake Cachuma for the years leading up to 2050.

3.1 Model Calibration Results

Using inputs of daily precipitation records from the rainfall station at Lake Cachuma and daily temperature measurements recorded at Lake Cachuma and Gibraltar for the period of 1980 to 2018, the ArcSWAT model was run to obtain streamflow for the upper SYR watershed. To determine the accuracy of the model, historical discharge recorded by USGS at Santa Cruz Creek was compared to simulated streamflow produced by ArcSWAT Santa Cruz Creek subbasin 1980 to 2018.

After examining historical Santa Cruz Creek discharge in comparison to the simulated streamflow, it was determined that the ArcSWAT model was overestimating streamflow for the Santa Cruz Creek sub-basin (Figure 28). ArcSWAT model parameters were evaluated and adjusted to more accurately reflect the hydrology of Santa Cruz Creek watershed and produce simulated streamflow more similar to historical observed discharge.

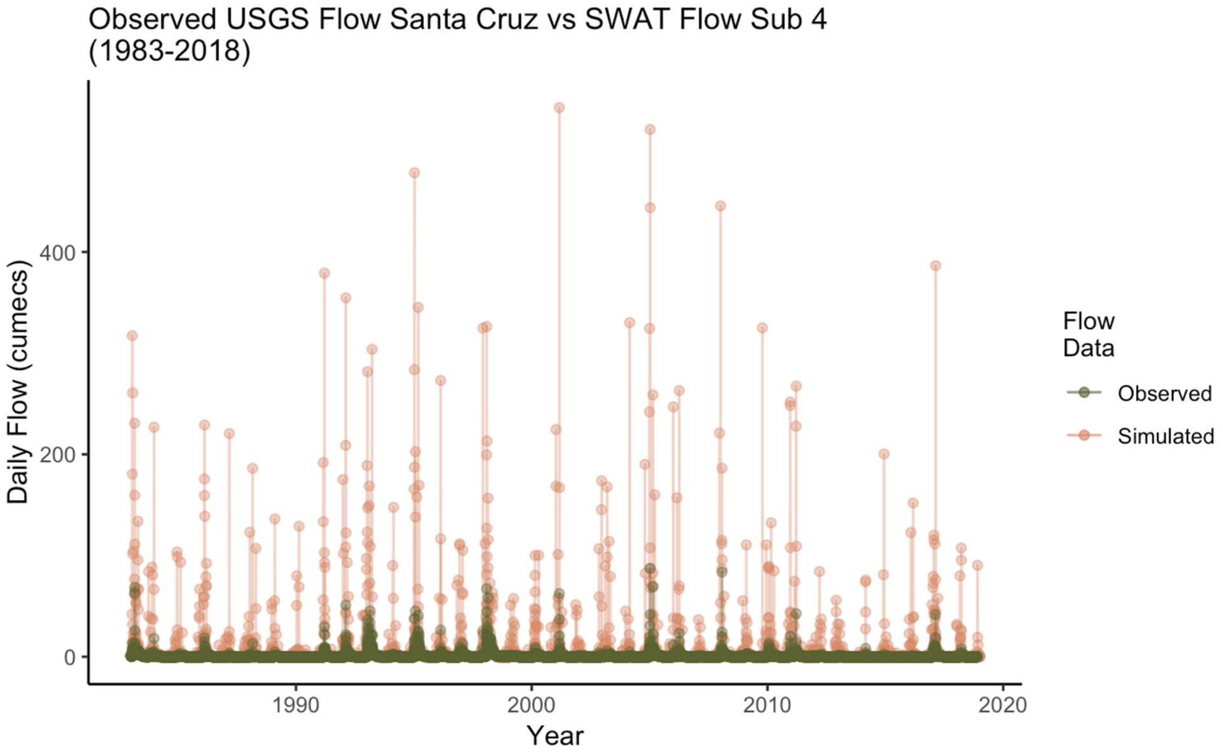

Figure 28. Comparison of SWAT Simulated Inflow and Observed Inflow Data for Sub-basin 4, 1983 - 2018. Observed flow data source: USGS Santa Cruz Creek flow gauge.

Eight model parameter adjustments were tested. Of these evaluations, four parameter changes were made: runoff curve number, hydraulic conductivity in the main channel, soil water availability capacity, and soil evaporation compensation factor. Parameters were manipulated to accurately reflect runoff and soil characteristics within the SYR watershed.

1. The runoff curve number encompasses soil permeability, land use, and antecedent soil water conditions throughout the entire watershed. The runoff curve number was decreased to a range of values from 35 to 70, varying based on different land use types present within the watershed. This is applicable for the SYR watershed because there tends to be less runoff in comparison to yearly precipitation based on examination of historical runoff ratios during the rainy season (Figure 29).

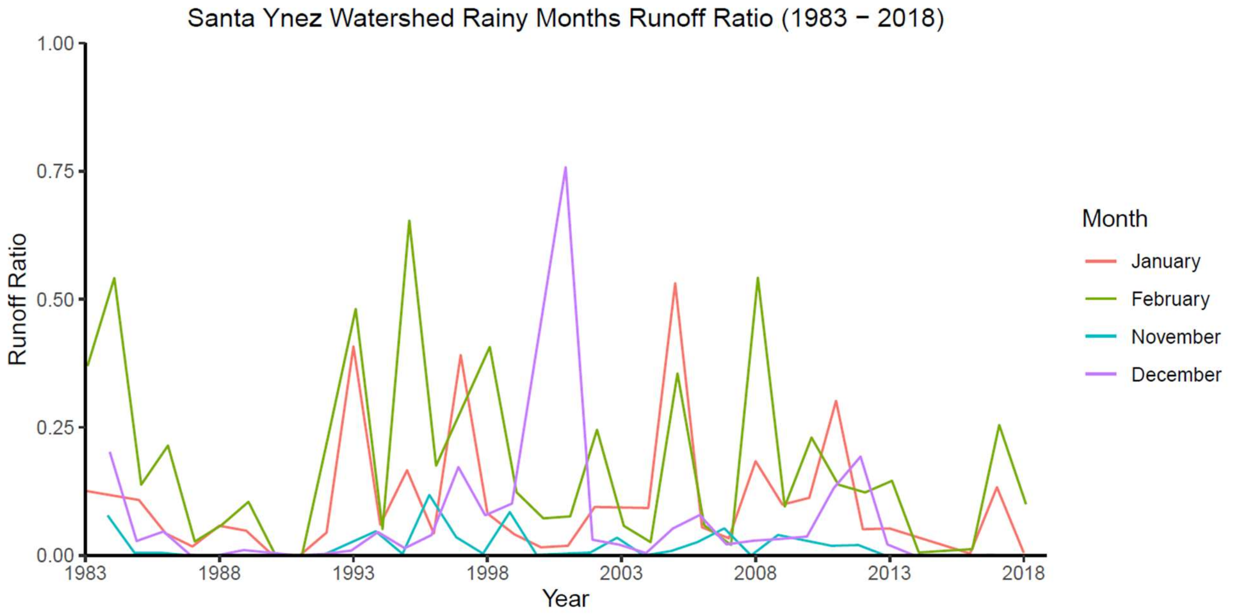

Figure 29. Yearly rates of runoff compared to precipitation for the Santa Ynez River watershed during the rainy season from 1983 to 2018. The runoff ratio describes the amount of precipitation that becomes surface runoff. Based on the runoff ratios, there tends to be low runoff associated with precipitation within the watershed during the rainy season. Precipitation obtained from the Santa Barbara County, Public Works Department Cachuma Dam Station; discharge obtained from the USGS Santa Cruz Creek flow gauge.

2. Hydraulic conductivity within the main channel describes the ease at which water flows through the channel bed's material, which is a function of hydraulic gradient and porosity and permeability of the bed material. The hydraulic conductivity within the main channel was increased to 100 millimeters per hour. As mentioned in Chapter 1, the upper SYR consists of step pools composed of large bed materials, which foster hydraulic resistance and turbulent flow. The presence of these step pools, along with the relatively large size of bed materials, may result in a relatively faster infiltration rate within the stream channel in comparison to other watersheds lacking step pools.
3. Soil available water capacity (AWC) refers to the volume of water that can be stored in soil and utilized by plants. To accurately reflect the range of soil AWCs represented in the SYR watershed, this parameter was increased by a factor of 0.2 for all soil types throughout the upper watershed to more precisely mirror estimated AWCs established through soil surveys and simulated discharge (Shipman 1981).
4. The soil evaporation compensation factor reflects the evaporative capability of the soil throughout the watershed, considering capillary forces and the physical features of the soil. This parameter was decreased by a factor of 0.5, supported by other ArcSWAT model calibration parameter changes used in Southern California (Xin 2018).

3.2 Model Fit

The final ArcSWAT calibration, displayed in Figure 30, aligns the simulated and observed Santa Cruz Creek discharge reasonably well, correctly predicting the timing of storm flow events, although the magnitudes of the simulated flows are consistently higher than the observed flows. Statistical testing, comparing average daily simulated and observed discharge, generates a 0.88 R^2 value and a 0.29 Nash-Sutcliffe Simulation Efficiency value. An R^2 value demonstrates the strength of the relationship between simulated and observed values, while the Nash-Sutcliffe indicates how closely the simulated and observed values fit a one-to-one ratio (Santhi 2007). These two statistical tests are the most common in characterizing hydrological model fit, and usually range from 0-1.

While the calibrated model appropriately generates runoff for Santa Cruz Creek during the correct time intervals, the model consistently simulates greater discharge in comparison to the discharge recorded by the Santa Cruz Creek gauge from 1980 to 2018. The high R^2 value is an indication of the well-calibrated relationship between simulated and observed discharge, while the lower Nash-Sutcliffe points to the over-stimulation during peak flow events. Despite this lower Nash-Sutcliffe value, it is within the range of satisfactory values (Moriasi 2007).

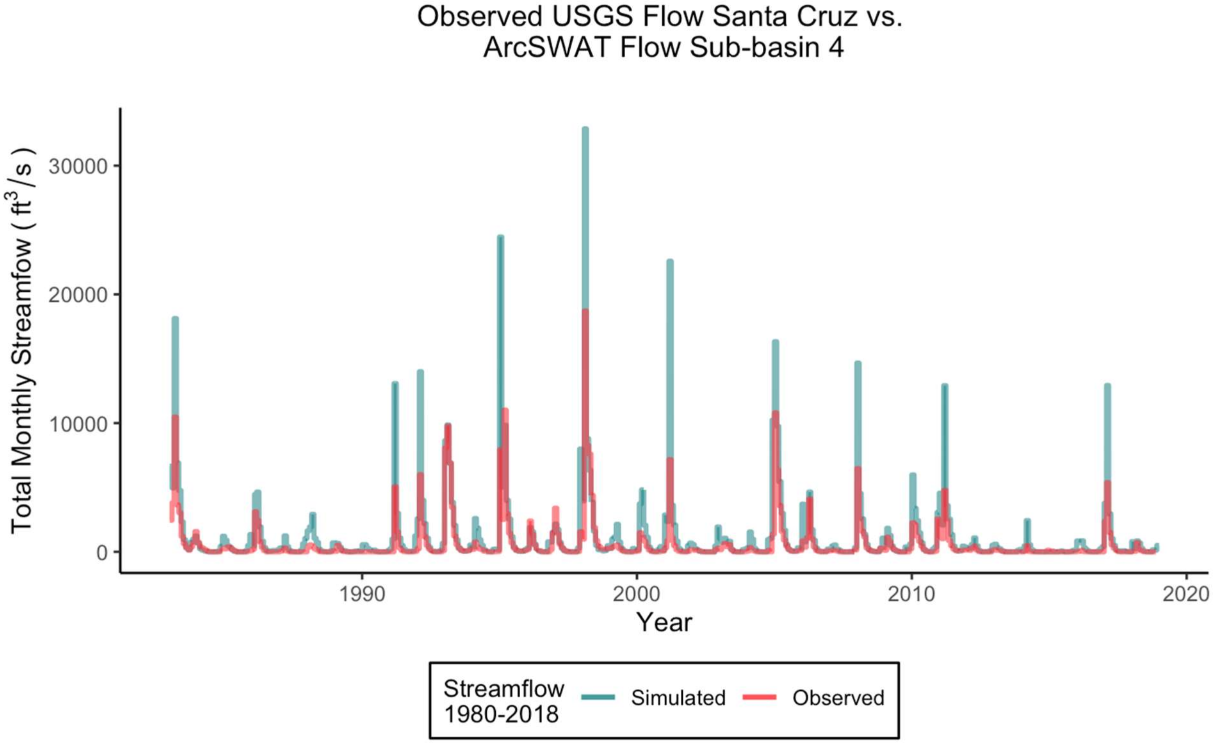

Figure 30. Monthly flow at Santa Cruz Creek compared to monthly simulated ArcSWAT Santa Cruz sub-basin flow (1980-2018). The red line depicts observed flow while the blue line represents the simulated ArcSWAT Santa Cruz flow after model calibration.

3.3 Model Results

Potential Changes in Streamflow due to Climate Change

The projected changes in streamflow indicate a wide range of possibilities depending on the climate model. Figure 31 displays the distribution of streamflow projected by each model for the entire simulated period (2020 - 2058),[24] and Figure 32 displays the distribution of streamflow projected by each model by decade. The climate model projections are displayed decadally to show the variability projected by each climate model over time; they do not predict what will happen in a specific decade. As shown in these boxplots, the extended drought model has both the lowest median streamflow and the smallest variation compared to the other models. Some decades have high variation in streamflow for each model while others have little variation. It is important to note that these climate models do not predict specific streamflow for a given time period but rather estimate possible future trends in streamflow.

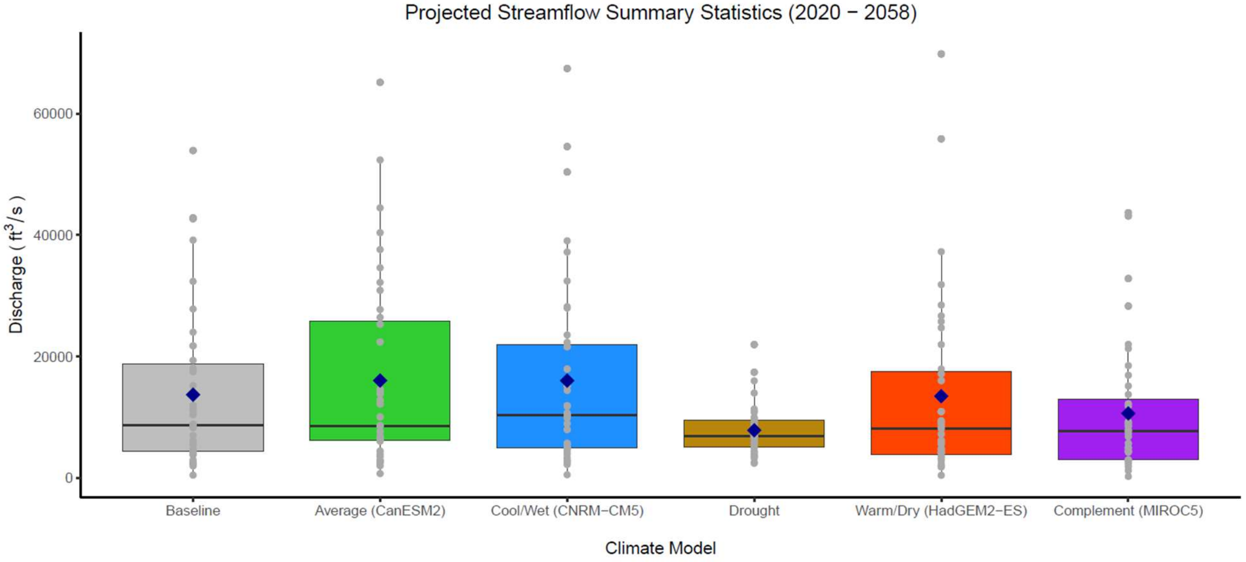

Figure 31. Summary statistics for projected streamflow for the five climate model scenarios and SWAT model baseline (2020 - 2058). The blue diamonds depict mean discharge, while the solid black horizontal line indicates the median discharge for each climate-projected streamflow. The grey dots display the projected yearly streamflow for each climate model scenario and the grey dots above the grey vertical lines are considered outliers. The lower and upper bounds of the box represent the 25th and 75th percentiles, respectively. Projection data gathered from Cal-Adapt.

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[24] See Appendix 7 for a table listing the summary statistic values associated with Figure 31.

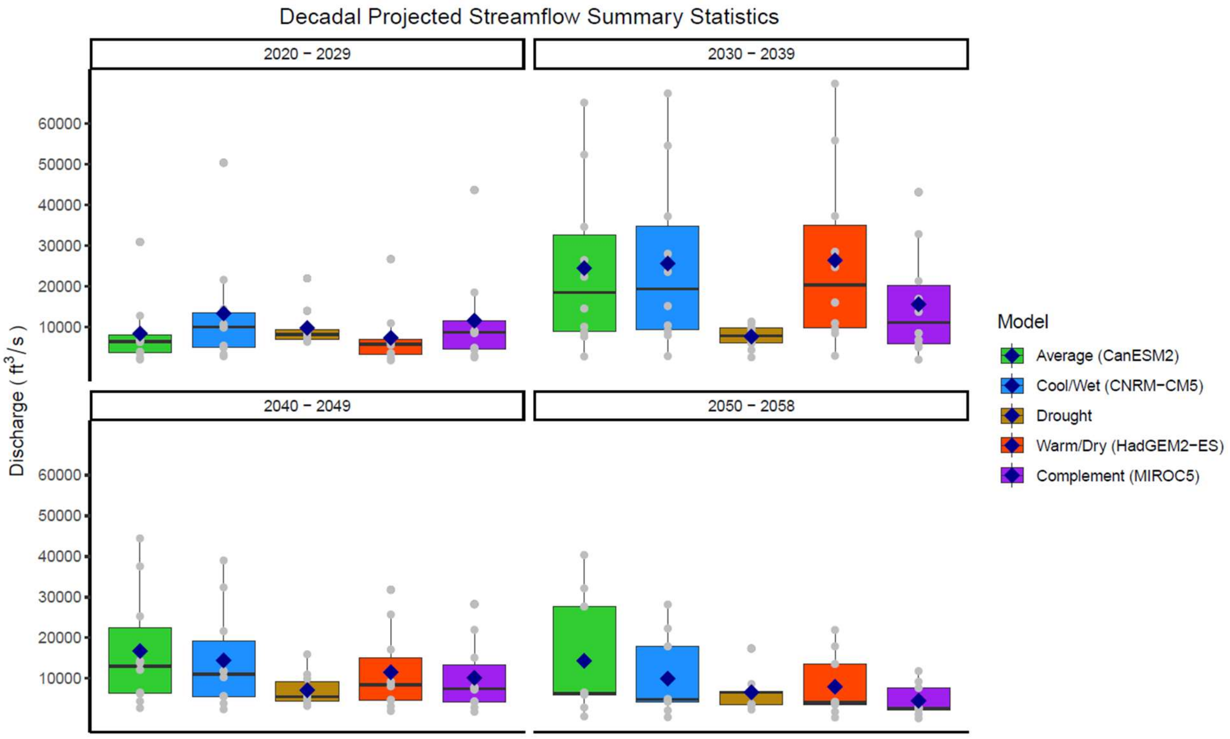

Figure 32. Summary statistics for projected streamflow for the five climate model scenarios by decade. The blue diamonds depict mean discharge, while the solid black line indicates the median discharge for each climate-projected streamflow. Other features as described for Figure 31. The climate model projections are displayed decadally simply to show the variability projected by each climate model over time; they do not predict what will happen in future decades. Climate change projection data gathered from Cal-Adapt.

Relative changes in projected future streamflow compared to the historical baseline (1980 - 2018) are summarized in Table 3. From 2020 to 2058, the lowest projected streamflow results from the extended drought model, indicating an average decrease of approximately 43%. The highest projecting model is the *average* model with an average increase of approximately 17%.

Table 3. Relative changes (%) in mean projected streamflow from 2020 to 2058 in Santa Cruz Creek (Subbasin 4) for future conditions as compared to historical baseline (1980 - 2018). Derived from 5 downscaled global climate models for emissions scenario RCP 8.5.

Model	**% Change from Baseline**
Warm/Dry (HadGEM2-ES)	-1.8
Average (CanESM2)	17.0
Cool/Wet (CNRM-CM5)	16.8
Complement (MIROC5)	-22.5
Drought	-42.9

Seasonality

Figure 33 shows observed and projected monthly precipitation aggregated across all years (2020 - 2058). Each model is projecting a decrease in total monthly precipitation compared to the historical baseline period (1980 - 2018). Among all models, the *warm/dry* and *complement* models are projecting the least amount of precipitation during the fall and early winter, while the extended drought model is projecting the highest amount of precipitation during this time period (2020 - 2058), indicating a seasonal shift. From winter through spring, the extended drought model is projecting the lowest amount of precipitation and the *average* and *cool/wet* models are projecting the highest amount of precipitation.

Unlike simulated results in total precipitation, some models project increases in total streamflow compared to the historical baseline. Figure 34 shows total monthly streamflow for each model simulation and the historical baseline. The *cool/wet* and *average* models project increases in streamflow compared to the historical baseline and the *complement* model is projecting a decrease in streamflow compared to the baseline. The extended drought model projects a slight increase in streamflow during the fall and early winter and the largest decrease in total streamflow of all the models during the winter and spring months.

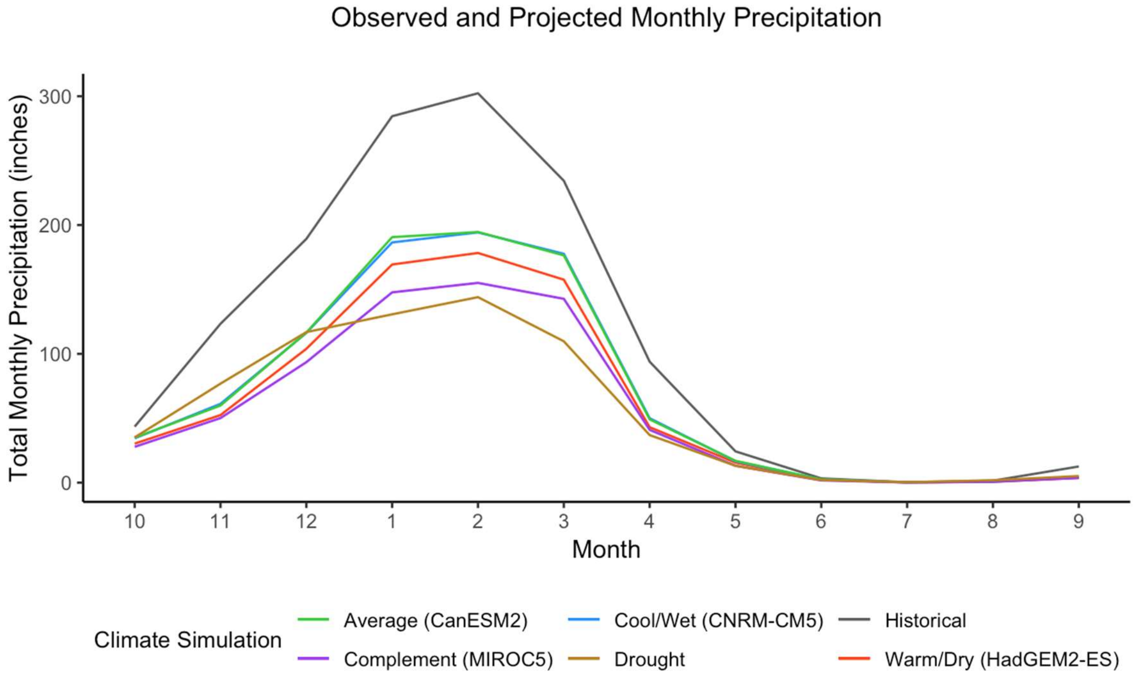

Figure 33. Observed and projected total monthly precipitation for each model. Observed precipitation data source: County of Santa Barbara, Lake Cachuma gauge, for years 1980-2018. Projection data gathered from Cal-Adapt for years 2020-2058.

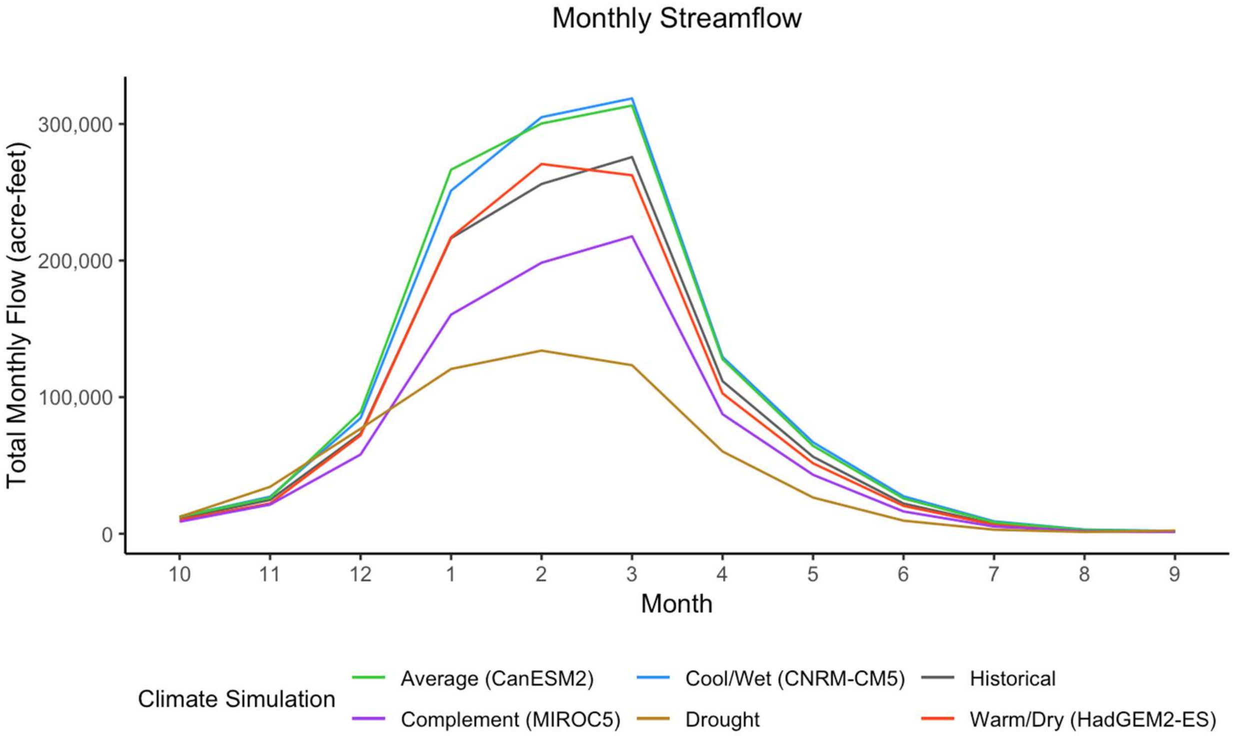

Figure 34. Observed and projected total monthly streamflow for each model (1980 - 2058). Observed streamflow data source: USGS. Projection data gathered from Cal-Adapt.

3.4 Upper Santa Ynez River & Reservoir Levels

Santa Cruz Creek simulated streamflow helps to characterize changes in discharge within the entire upper SYR watershed under the five climate model scenarios. Each sub-basin in the upper Santa Ynez is somewhat different in slope, rainfall received, seasonal temperatures, soil types, vegetation, and land use. However, extrapolations beyond Santa Cruz Creek sub-basin are used here to provide ranges of possible total upper SYR yearly discharge under each climate model scenario. These ranges in streamflow therefore indicate total inflow estimates into Cachuma Reservoir.

To most appropriately extrapolate Santa Cruz Creek streamflow to the entire upper SYR, historical Santa Cruz Creek discharge contribution to total Cachuma Reservoir inflows were estimated. To accomplish this, the Cachuma Operations and Maintenance Board's (COMB) Cachuma Reservoir mass balance was normalized for inflows and outflows depicted in the equation below:

Normalized Cachuma Monthly Total Storage = *Storage Volume – (Precipitation + Imported Water (CCWA)) + (Evaporation + Seepage + Managed Releases + Spills)*

Normalized Cachuma monthly total storage was then used to find the change in monthly storage using the following equation:

> ***Total Monthly Inflow to Cachuma*** *= Normalized Cachuma Monthly Storage - Normalized Cachuma Monthly Storage for Following Month*

> Example: *February Inflow to Cachuma = Normalized Cachuma February - Normalized Cachuma January*

Total monthly inflow to Cachuma was then compared to total monthly inflows from Santa Cruz Creek with the following equation:

> ***Santa Cruz Creek Percent*** *= Total Monthly Inflow Supplied by Santa Cruz Creek (AF) / Total Monthly Inflow to Cachuma*

Because changes to storage in Cachuma Reservoir are commonly net-negative, only the rainy season months, December through May, where a positive change in storage occurred, were considered. The percent that Santa Cruz Creek contributes to Cachuma Reservoir monthly increases in storage during the rainy months was compared across all years included in the provided COMB Cachuma Reservoir mass balance (1999 - 2017) (Figure 35).

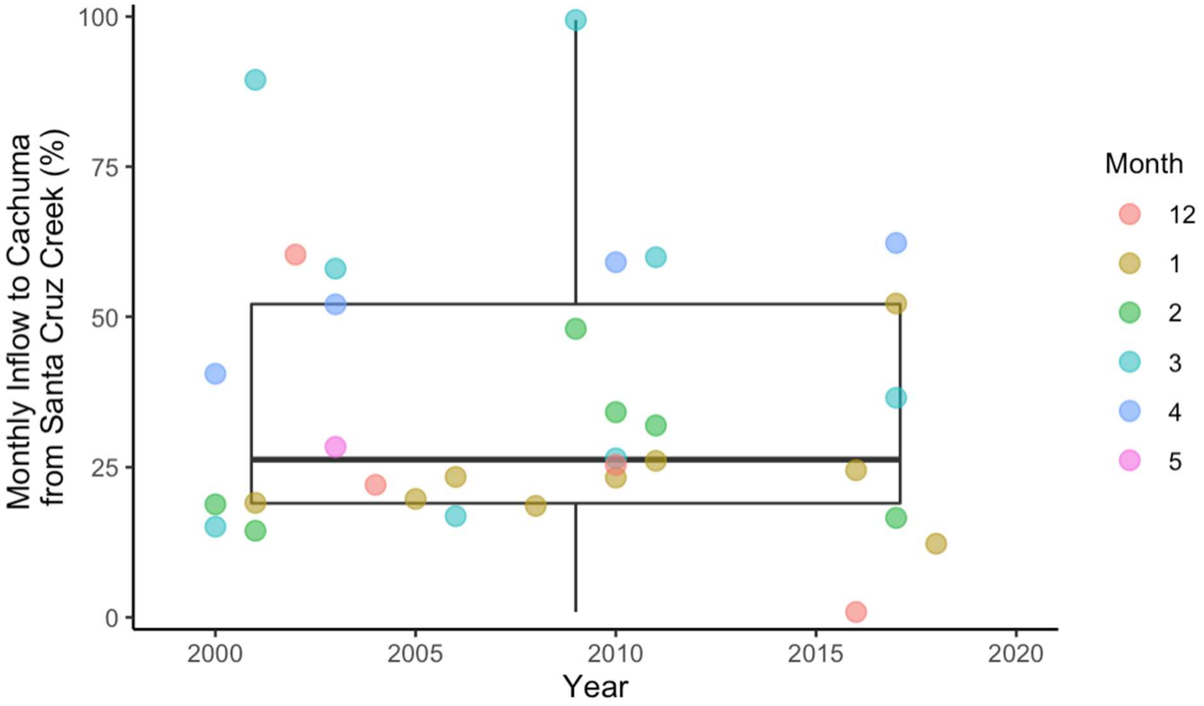

Figure 35. Percentage of total Cachuma inflow that Santa Cruz Creek discharge contributed during the rainy season by month (1999 - 2017). Each point, colored by month, represents the percent that Santa Cruz Creek inflow contributed to total Cachuma inflow during that month. The box represents the 25th percentile, median and 75th percentile, with minimum and maximum points ranging from 0-100%. Data sources: Cachuma and Operations Maintenance Board and USGS. Accessed September 2019.

The amount that Santa Cruz Creek contributes to monthly inflows to Cachuma varied. While this analysis indicates that Santa Cruz Creek may contribute up to 100% of the inflow into Cachuma during the month of March, this cannot be accurate due to the numerous other creeks and groundwater discharge areas also contributing to Cachuma levels. Despite the data limitations, this analysis indicates that Santa Cruz Creek flows contribute to Lake Cachuma inflows to varying degrees.

Considering this variability, the 25th percentile, ~20%, and 75th percentile, ~50%, were used as the range of factors of proportional monthly Santa Cruz Creek discharge to estimate yearly total upper SYR watershed inflow into Cachuma. Only rainy months from December through May were incorporated into the aggregated values defining the box plots in Figure 36 and 37.

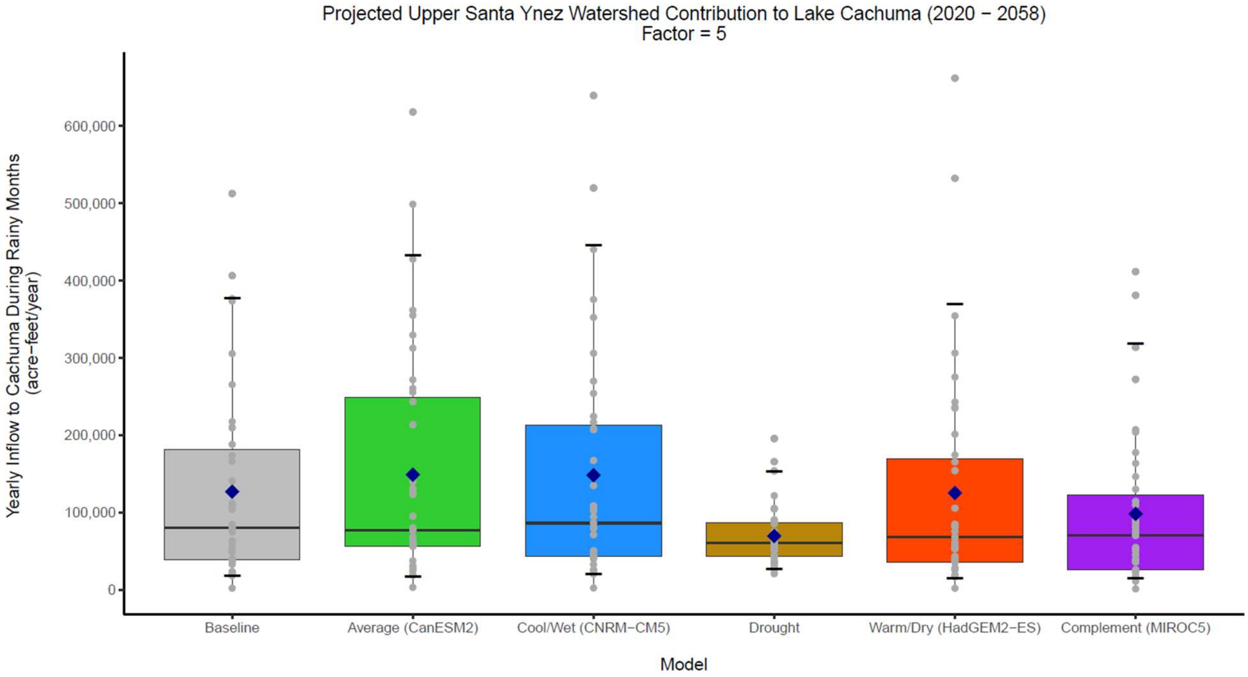

Figure 36. Projected upper Santa Ynez River watershed streamflow contribution to Lake Cachuma (2020 - 2058). The factor of 5 refers to historical Santa Cruz Creek discharge contributing to ~20% of Lake Cachuma's inflows. The blue diamond represents the yearly mean projected Cachuma inflow for each climate model. The solid black line depicts the yearly median projected Cachuma inflow for each climate model. The upper and lower black dashes represent the 5th and 95th percentiles, respectively, of yearly projected Cachuma inflow for each climate model.

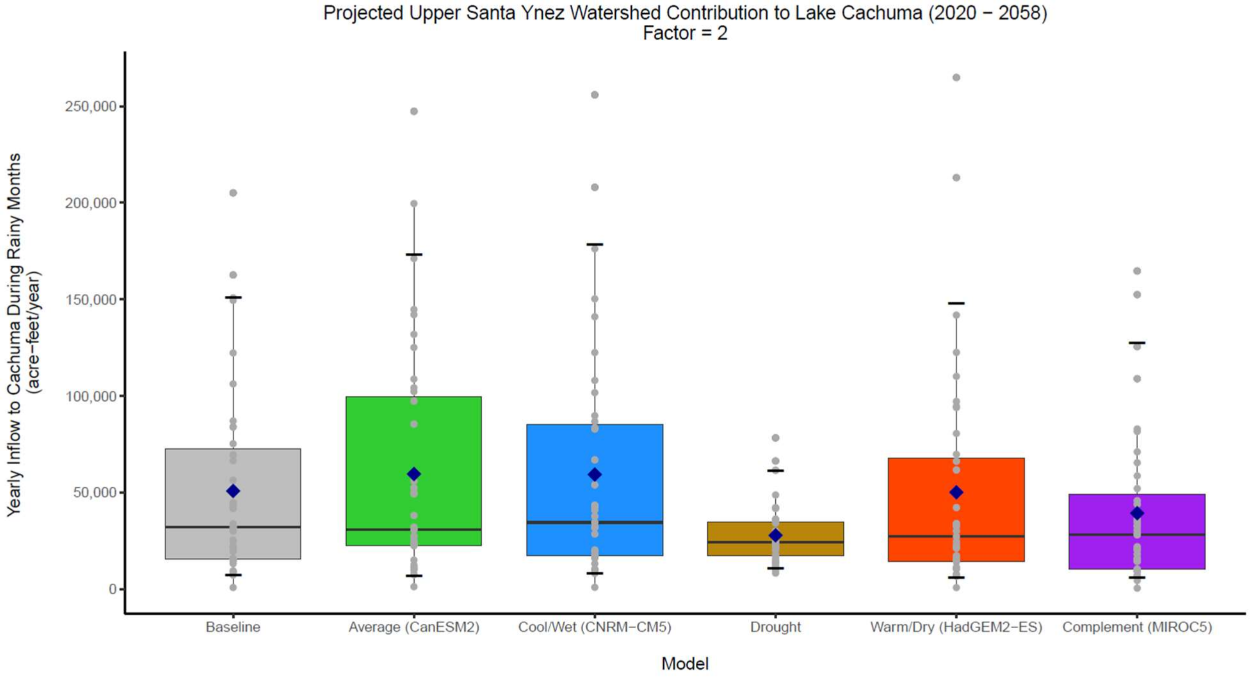

Figure 37. Projected upper Santa Ynez River watershed streamflow contribution to Lake Cachuma (2020 - 2058). The factor of 2 refers to historical Santa Cruz Creek discharge contributing to ~55% of Lake Cachuma's inflows. The blue diamond represents the yearly mean projected Cachuma inflow for each climate model. The solid black line depicts the yearly median projected Cachuma inflow for each climate model. The upper and lower black dashes represent the 5th and 95th percentiles, respectively, of yearly projected Cachuma inflow for each climate model.

The 25th percentile of historical Santa Cruz Creek inflow contribution to Lake Cachuma estimates that the upper SYR watershed can supply about 20% of Lake Cachuma's water availability in a given year. Using this observation and the range of yearly discharge produced for each climate model, total yearly Cachuma inflow can be roughly estimated (Figure 36). Under this assumption, for a given year within the period of 2020 to 2058, Lake Cachuma may receive a range of inflows from the upper Santa Ynez watershed, ranging in value from ~0 to 650,000 acre-feet per year.

It is important to consider the projected upper SYR watershed contribution values that lie within the interquartile range, as the range between the 25th and 75th percentiles represents the highest concentration of data points. When considering the interquartile range, the upper SYR watershed could contribute ~50,000 to 250,000 acre-feet per year to Lake Cachuma. Interestingly, the median upper SYR watershed contribution to Lake Cachuma is similar across all climate models, ranging from ~75,000 to 90,000 acre-feet.

The baseline upper SYR watershed inflow contribution to Lake Cachuma is based on SWAT-simulated streamflow for the Santa Cruz Creek sub-basin, aggregated by year for the time period of 1980 to 2018. The baseline is included in Figures 36 and 37 to compare future simulated upper SYR watershed contribution to historical simulated inflow contribution to Lake Cachuma. In comparison to the baseline, the *average*, *cool/wet*, and *warm/dry* models portray a greater range in potential upper SYR watershed inflow contribution to Lake Cachuma. The extended drought and *complement* models display a smaller range in inflow contribution to Lake Cachuma when compared to the baseline.

When considering potential outliers for upper SYR watershed contribution to Lake Cachuma (represented by the gray points above the gray lines bisecting each boxplot in Figures 36 and 37), the greatest range in estimated yearly contribution across all climate models is for the *warm/dry* model. However, the *cool/wet* model follows closely behind, exhibiting a similar range in inflow contribution to Lake Cachuma.

The greatest interquartile range for the estimated yearly upper SYR watershed inflow contribution to Lake Cachuma for the time period of 2020 to 2058 is for the *average* climate model (Figure 36). In contrast, the extended drought model exhibits the smallest interquartile range in estimated yearly inflow to Lake Cachuma. Notably, the *warm/dry* model depicts a similar interquartile range for the estimated yearly upper SYR watershed inflow contribution to Lake Cachuma in comparison to the baseline.

In contrast to the 25th percentile of historical Santa Cruz Creek inflow contribution to Lake Cachuma, the 75th percentile estimates that about 55% of Lake Cachuma's yearly water inflow could be provided by the upper SYR watershed (Figure 37). Under the prediction that the upper SYR watershed can contribute 55% of inflow to Lake Cachuma, the potential inflow for a given year during the time period of 2020 to 2058 ranges from ~0 to 250,000 acre-feet across all climate models. The yearly projected median contribution to Lake Cachuma varies, as it is between ~25,000 and 35,000 acre-feet for each climate model.

The 20% and 55% upper SYR watershed inflow contribution to Lake Cachuma estimates were obtained by examining historical Santa Cruz Creek inflow data during the rainy season months of December through May. Figure 38 depicts the percentage difference between the projected values for the upper SYR watershed inflow contribution to Lake Cachuma under each climate model and the simulated baseline for the time period of 2020 to 2058. SWAT-simulated daily streamflow for the baseline and each climate model were aggregated on a yearly basis using only the rainy season months of December through May. Based on this calculation, the extended drought model estimates the greatest decrease in yearly upper SYR watershed inflow to Lake Cachuma. The extended drought model estimates that within a given year, the greatest potential decrease in upper SYR watershed streamflow contribution to Lake Cachuma could be ~200% in comparison to the yearly inflow contributed from the baseline run under current climatic conditions for the same time period. The extended drought model also provides the greatest range in potential percentage difference from the baseline run for a given year during the model-simulated time period, with the percent difference in streamflow contribution ranging from ~ -200% to ~ 10%. In contrast, the *average*, *cool/wet*, *warm/dry*, and *complement* climate models estimate an increase in the inflow contribution to Lake Cachuma by the upper SYR watershed. Among the 4 models, this potential increase in inflow to Lake Cachuma ranges from a ~0 to 20% increase in a given year in comparison to the baseline model run.

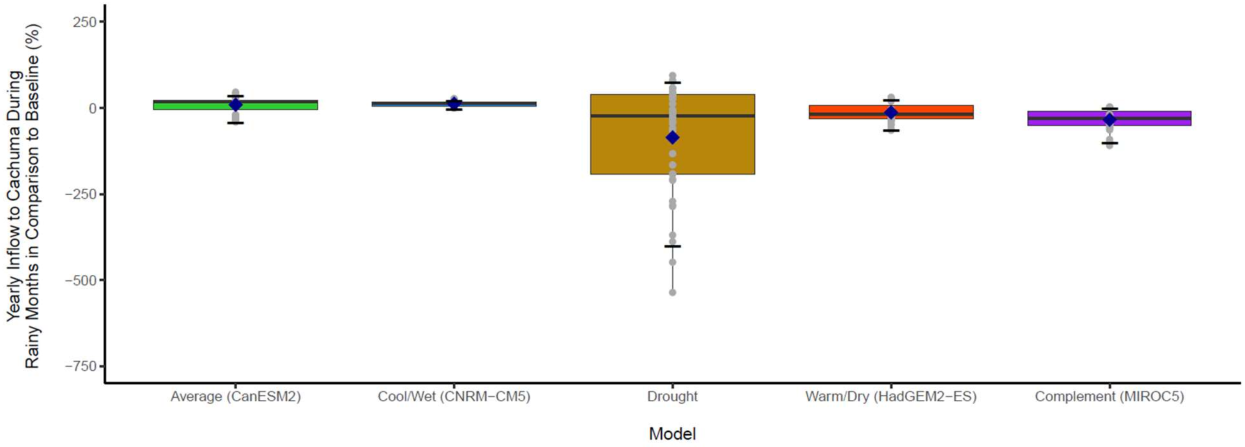

Figure 38. Projected percentage change of upper Santa Ynez River watershed contribution to Lake Cachuma for 2020 - 2058, in comparison to simulated baseline streamflow for 1980 to 2018. The blue diamond represents the yearly mean projected percentage difference in Cachuma inflow between each model and the baseline. The solid black line depicts the yearly median projected percentage difference in Cachuma inflow between each model and the baseline. The black dashes represent the 5th and 95th percentiles of yearly projected percentage differences in Cachuma inflow between each model and the baseline. A projected percent change of -1000% for the extended drought model is not depicted. Refer to Appendix 8 for individual projected percentage change figures.

Chapter 4. Discussion

4.1 Sedimentation

Sedimentation of Gibraltar Reservoir has limited its water storage capacity, as discussed in Chapter 1, and the effects of climate change are likely to alter sedimentation within the reservoir in the future. Sedimentation of Gibraltar has varied based on the number of large precipitation events and wildfires occurring in the watershed. In 2017, the average annual sediment inflow was estimated to be 210 AFY since the dam's original construction in 1920, but varies due to major fire events and high flow flushing events (Holt 2016). The current capacity of the reservoir is estimated to be ~30% of its original capacity of 15,000 AF in 1920 (County of Santa Barbara 2020). The current capacity of Lake Cachuma is ~193,000 AF, or 72% of the original capacity (County of Santa Barbara 2020). In contrast to Gibraltar, Lake Cachuma does not face as much sedimentation since water from the SYR flows into Gibraltar first, forcing this reservoir to act as a sediment trap.

Shifts in temperature and precipitation in the future as a result of climate change may alter the sedimentation rate within Gibraltar. Cal-Adapt maximum temperature projections under RCP 8.5 indicate that local temperature may increase in the future (Cal-Adapt 2019). Increases in temperature, coupled with the possibility of subsequent increased aridity, can exacerbate the characteristics that commonly promote wildfires (Westerling et al. 2011). Future precipitation patterns under a changing climate are more difficult to anticipate, as historical precipitation in the watershed is highly variable (Oakley et al. 2018). Some climate projections and studies imply that high intensity precipitation events may occur more frequently in mediterranean climate regions in the future (Swain et al. 2018).

The combination of a potentially warmer, more arid climate, and increasingly variable and intense precipitation events, will alter discharge and affect sediment flow into Gibraltar Reservoir. The occurrence of heavy rainfall events following large wildfires can mobilize post-wildfire debris flows, increasing sedimentation in the SYR watershed's local surficial reservoirs. Depending on the frequency of relatively large wildfires and subsequent heavy precipitation events, the rate of sedimentation into Gibraltar may be altered in the future.

4.2 Seasonality

The timing of streamflow has important implications for water availability and competition for water supply during months with decreased streamflow (Hamlet and Lettenmaier 1999). Most of the western United States has experienced a shift toward earlier springtime snowmelt and streamflow (Stewart et al. 2005). Though studies have linked warmer temperatures, especially during the winter and spring, to shifts in the timing of snowmelt and subsequent streamflow, there is more uncertainty regarding the effect that changes in precipitation may have on streamflow (Stewart et al. 2005). One study indicates that while changes in temperature shift the timing of streamflow, changes in precipitation alters the volume of runoff (Hamlet and Lettenmaier 1999). As described in Chapter 1, historical trends in precipitation show far more variation than temperature. The climate models used in this analysis project increases in temperature over time, whereas the projected changes in precipitation range from an increase of approximately 33% to a decrease of about 28% (Appendix 4).

As shown in Chapter 3, over the entire simulated time period (2020 - 2058) all models are showing a decrease in total precipitation compared to the historical baseline (Figure 33). The volume and timing of precipitation may have larger implications on water availability in the SYR watershed. Decreasing precipitation in combination with increasing temperatures, which increase evaporation rates, can reduce water availability and increase water demand (U.S. EPA nd). Although it is beyond the scope of this project, it is important to further investigate potential shifts in the seasonality of precipitation and streamflow to more precisely anticipate potential impacts to water availability.

4.3 Water Supply Sources

Groundwater

Assessing the potential impacts of climate change on the Santa Barbara[25] and Foothill groundwater basins (Figure 39) are important to support holistic water management efforts for the City. The Santa Barbara and Foothill groundwater basin lies within a two mile area between the Santa Ynez Mountains and the Pacific Ocean (Nishikawa et al. 2018). A USGS study conducted by Nishikawa et al. (2018) examined how to best maintain sustainable yield through modeling the Foothill and Santa Barbara groundwater basins. The USGS implemented the Santa Barbara Flow and Transport Model (SBFTM) to simulate seawater intrusion under various management strategies (Nishikawa et al. 2018). The SBFTM is a three-dimensional density-dependent groundwater-flow and solute-transport model (Nishikawa et al. 2018).

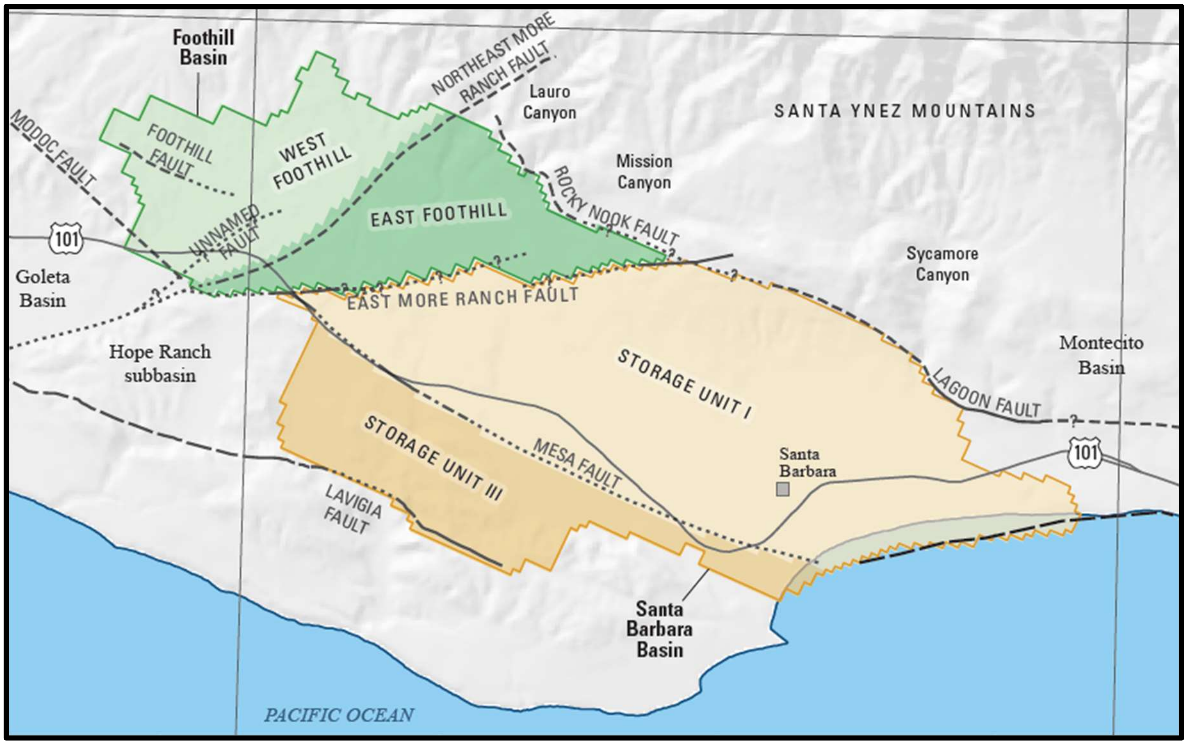

Figure 39. The City of Santa Barbara groundwater basins. Source: Santa Barbara and Foothill Groundwater Basins Geohydrology and Optimal Water Resources Management - Developed Using Density Dependent Solute Transport and Optimization Models 2018.

During dry periods, the City has used groundwater to supplement up to 20 - 25% of the total water supply (Mauceri 2019). In 2015, water levels at a monitoring well[26] fell 120 feet below NAVD

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[25] The Santa Barbara basin includes Storage Unit I and Storage Unit III.

[26] Monitoring well 4N/27W-08M6 located in the Eastern part of the Foothill Subbasin (Nishikawa et al. 2018).

88[27,28] after a period of over pumping (Nishikawa et al. 2018). In 2004, the same monitoring well peaked at 180 feet above NAVD 88, indicating that the City's pumping rates vary depending on the length and severity of dry periods. Between 1991 - 2006, pumping decreased significantly allowing groundwater reserves to recover by 10,800 AF (Nishikawa et al. 2018). The City tracks groundwater levels to ensure that it does not reduce overall groundwater storage.

Tracking groundwater levels can be especially important for groundwater wells closer to the coast. Monitoring wells ranging from 200 to 1,300 ft from the ocean had increased saltwater intrusion when well water levels decreased below the sea level of the coast (Nishikawa et al. 2018). Between 1985 and 1991, increased pumping caused greater salinity in monitoring wells in the Santa Barbara groundwater basin (Nishikawa et al. 2018). Saltwater intrusion was estimated by the elevated concentrations of chloride present at the monitoring wells (Figure 40) in the Santa Barbara groundwater basin (Nishikawa et al. 2018). Storage Unit I of the Santa Barbara groundwater basin is known to be the most susceptible to saltwater intrusion during periods of over pumping (Water Resource Division, Public Works Department 2011).

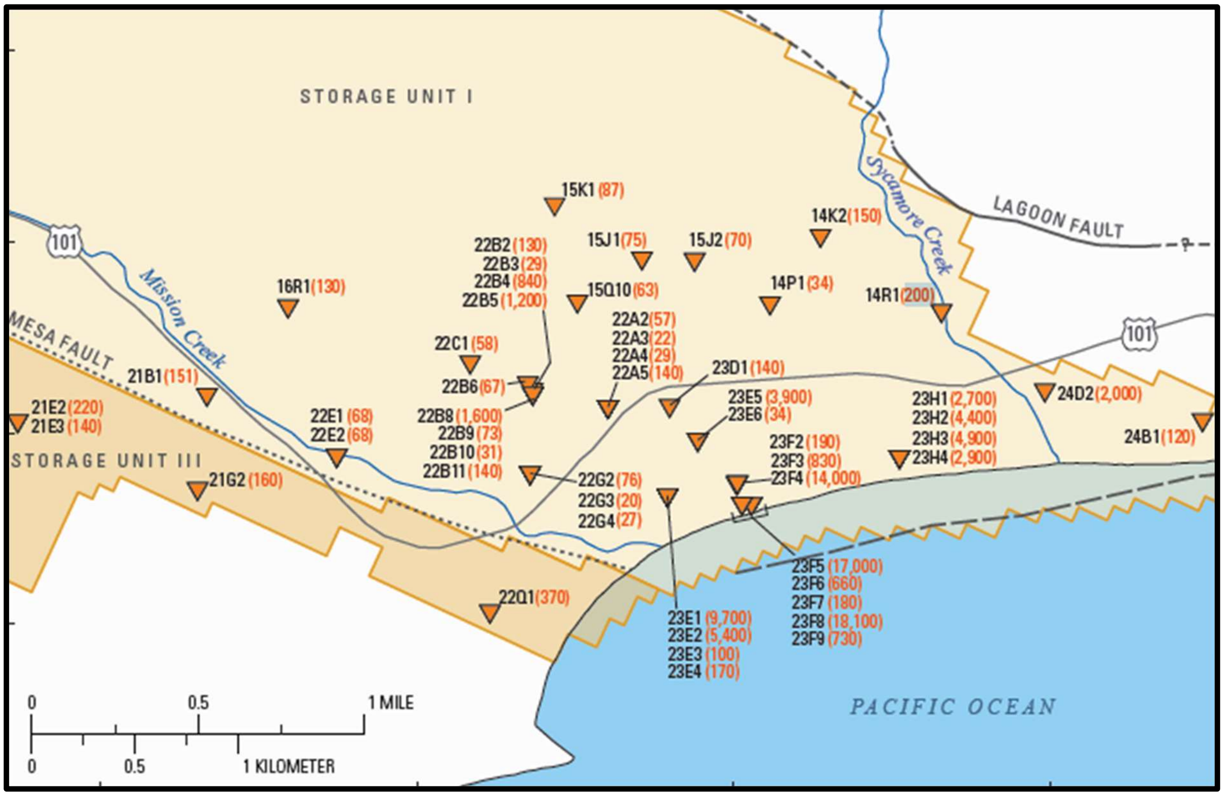

Figure 40. Chloride concentrations at monitoring wells for Santa Barbara groundwater basin. The number in parenthesis is chloride concentration present at the monitoring wells in milligrams per liter. Source: Santa Barbara and Foothill Groundwater Basins Geohydrology and Optimal Water Resources Management - Developed Using Density Dependent Solute Transport and Optimization Models 2018.

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[27] The reported elevation of the report is the distance above the vertical datum NAVD 88 (Nishikawa et al. 2018).

[28] NAVD 88 holds the fixed height for the primary tidal benchmark (National Geodetic Survey 2018).

Under optimal pumping conditions[29] saltwater intrusion to Storage Unit I has declined due to the flow of the basin going towards the ocean and an offshore fault that acts as a barrier for groundwater flow (Nishikawa et al. 2018; Water Resource Division, Public Works Department 2011). Relocation of wells, decreased pumping, and artificial recharge would reduce salt water intrusion in the basin (Nishikawa et al. 2018).

Maintaining the groundwater level above sea-level will become increasingly more difficult if sea-level continues to rise. The 2018 State of California Sea-Level Rise Guidance Report estimated that for RCP 8.5, by 2100, there is a 89% chance of sea-level rising by one foot, 53% chance of sea-level rising by two feet, and a 19% chance of sea-level rising by three feet for the Santa Barbara area (California Natural Resource Agency & California Ocean Protection Council 2018). There are numerous pumping wells[30] less than a mile from the ocean. Sustainable pumping yields and managing groundwater levels will be crucial to avoid salt-water intrusion at the coastal boundary of the basin.

Sustainable pumping yields is equally important for offsetting land subsidence[31]. Subsidence causes degradation of the groundwater aquifer, ultimately resulting in loss of groundwater storage (Walton 2017). The study conducted by Nishikawa et al. (2018) did not detect land subsidence in the Foothill and Santa Barbara groundwater basins. Using the results of the USGS study, the City developed a comprehensive groundwater pumping plan that focuses on sustainable pumping yields to prevent groundwater level declines and saltwater intrusion (City of Santa Barbara Water Resources Division 2019).

The City developed a 10 year pumping plan[32] establishing the sustainable yield for Storage Unit 1 and Foothill Basin as 16,090 AF and 8,130 AF, respectively (Water Resource Division, Public Works Department 2019). Taking into account previous pumping since 2011, the remaining pumping for Storage Unit 1 and Foothill Basin to remain within the sustainable yield established by the 10 year pumping plan is 10,280 AF and 3,816 AF, respectively (Water Resource Division, Public Works Department 2019). According to the 2011 LTWSP, the City will manage basins to maximize available storage and as a backup water supply sources during drought periods (Water Resource Division, Public Works Department 2011). Successful groundwater management hinges on how well the City can maintain groundwater storage during prolonged dry periods, decreasing wet seasons, increased storm intensity, and saltwater intrusion.

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[29] This is a condition under normal pumping or no pumping within Storage Unit 1 (Nishikawa et al. 2018).

[30] Production wells within a mile of the ocean include Vera Cruz (22B6), City Hall (22C1), Corporation Yard (15Q10), and Ortega Park (15J2) wells (Nishikawa et al. 2018).

[31] The sinking of the ground due to underground movement of materials such as water, oil, and natural gas. Removal of these materials is often the cause of land subsidence (NOAA 2019).

[32] The City of Santa Barbara Water Supply Management Report incorporated a 10 year pumping plan based off modeling data received from a 2018 USGS report of the groundwater basins (City of Santa Barbara Water Resources Division 2019).

The SBA-CEVA, a recent Santa Barbara area coastal ecosystem vulnerability assessment report, concluded that the wet seasons are projected to be 7 - 8% shorter during 2006 - 2061 and roughly 10 - 15% shorter during 2045 - 2100 (Myers et al. 2017). The wet season is projected to begin later and end sooner, decreasing the opportunity for the Santa Barbara area to receive precipitation (Myers et al. 2017). The amount of precipitation available will directly affect the areal recharge[33] rate of the Santa Barbara and Foothill groundwater basins. A shorter wet season combined with variability in precipitation can decrease total annual precipitation[34] over the Santa Barbara groundwater basin. The SBA-CEVA report projects that the intensity of storms will increase for the Santa Barbara area (Figure 41). Having larger rain events potentially translates to higher peak discharge[35] and more runoff.[36,37] The mean annual stream discharge and mean annual peak streamflow is estimated to increase by 10 - 20% from 2006 - 2061 and 20 - 40% during 2045 - 2100 (Myers et al. 2017).

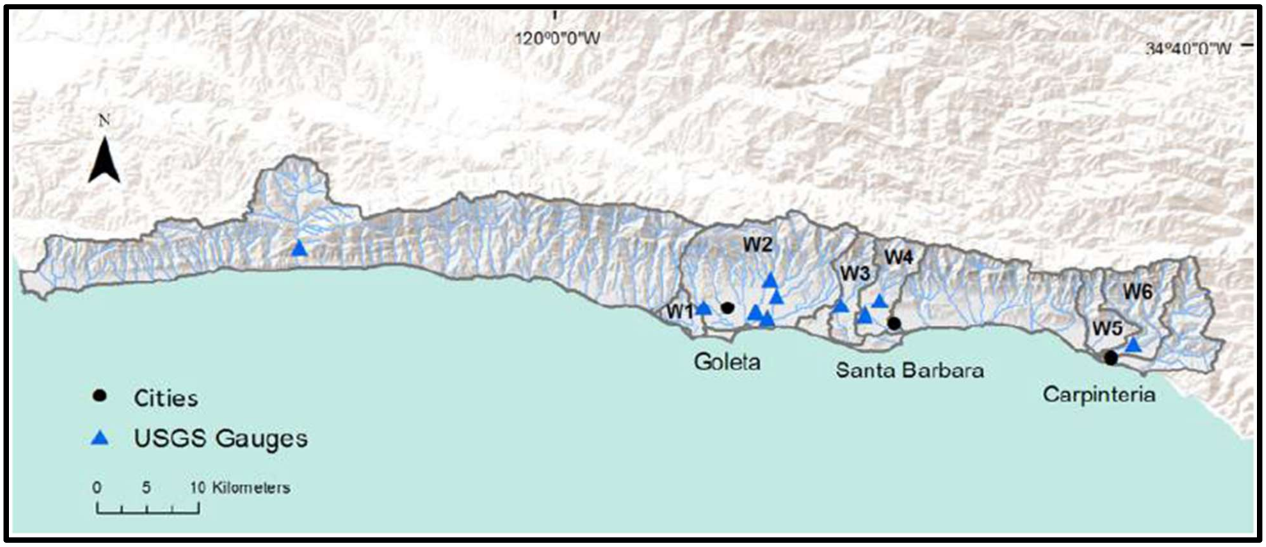

Figure 41. The SBA-CEVA watershed analysis. The SBA-CEVA study region consists of Devereux Slough (W1), Goleta Slough (W2), Arroyo Burro (W3), Mission (W4), Santa Monica/Franklin (W5), and Carpinteria (W6). Source: SBA-CEVA Report 2017.

With shorter wet seasons and increased storm intensity, opportunities for groundwater water recharge will decrease. Heavy rainfalls quickly exceed the infiltration capacity[38] (SARE 2012). Steady state infiltration[39] is achieved when the soil is nearly saturated and can be maintained under low intensity precipitation events (USDA-NRCS 2014). Conversely, low intensity precipitation

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[33] Areal recharge is defined as the amount of direct infiltration from precipitation (Nishikawa et al. 2018).

[34] Average annual precipitation for the Foothill and Santa Barbara groundwater basin is currently 18.55 inches a year (Nishikawa et al. 2018).

[35] Due to large rainfall events on wetter soils (Myers et al. 2017).

[36] Due to wetter initial conditions (Myers et al. 2017).

[37] Runoff is defined as rain that is unable to infiltrate the soil due to soil saturation (USGS 2018).

[38] The amount of water that can infiltrate the soil before coming runoff (SARE 2012).

[39] Infiltration rate does not increase or decrease if more water is added (USDA-NRCS 2014).

generates more groundwater recharge as it allows the soil to become saturated enough to allow for infiltration (Tashie et al. 2015). Recharge for the Santa Barbara groundwater basin is primarily through creeks[40] and the Santa Ynez Foothills (Nishikawa et al. 2018). It is estimated that ground water recharge from creeks is 925 AFY and Santa Ynez Foothills to be 300 AFY (Nishikawa et al. 2018). Depending on the creek location it can either be a source of recharge or discharge[41]. Groundwater discharge is estimated to be as high as 1,700 AFY which is a total net loss of 775 AFY from groundwater to creeks (Nishikawa et al. 2018).

Water retention strategies for the purpose of groundwater recharge has been widely incorporated throughout Southern California. Such as a spreading basin which holds surface water and allows it to infiltrate the groundwater aquifer (NGWA 2020). Yet, due to a clay cap[42] present in the City groundwater basin, conventional runoff management systems cannot recharge the groundwater basin (Corey 2020). The clay cap is not present within the Santa Ynez Foothills and creeks which is why groundwater recharge occurs in these locations (Corey 2020). However, bioretention[43] systems can be helpful when it comes to storing water in the surfaces soil, which reduces the amount of water needed for landscaping (Corey 2020).

Desalination

Desalination currently plays a crucial role in supplementing the City water supply. In 2017, the City began distributing water to residents after the Charles E. Meyer Desalination Plant was re-commissioned after being placed in stand-by[44]mode (City of Santa Barbara 2020). The desalination plant has the highest energy needs compared to the City other water supply sources (City of Santa Barbara Water Resources Division 2011). Desalination energy consumption makes up 44%[45] of the total water production costs (Al-Karaghouli & Kazmerski 2013). The desalination plant has been retrofitted with the most recent technological advancements that include improved filter technology and high efficiency pumps to reduce the energy demand and environmental impacts associated with desalination (City of Santa Barbara 2020).

Minimizing environmental impacts such as brine, is important as expanding the desalination plant may become necessary to meet future water demand. Brine[46], a by-product of the desalination process, can harm bottom-dwelling marine life (Cooley et al. 2013). The City currently blends

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[40] Creeks that provide groundwater recharge: Mission, Sycamore, Arroyo Burro, San Roque, Cieneguitas, and Atascadero (Nishikawa et al. 2018).

[41] Groundwater discharge describes the movement of water from the subsurface area to the surface. Discharge can naturally happen in lakes, stream, and creeks (University of Calgary 2012).

[42] The clay cap does not allow for infiltration from the surface to reach the deep basin (Corey 2020).

[43] Bioretention systems are typically vegetated ponding areas that provide space to capture stormwater runoff and time to allow the captured water to infiltrate (Zhang & Guo 2014).

[44] The desalination plant will be placed in a non-operational mode to reduce cost when desalination is not needed to supplement the water supply.

[45] This cost is for desalination plants utilizing reverse osmosis membranes, thermal distillation plants have a much higher cost closer to 60% of total water production costs (Al-Karaghouli & Kazmerski 2013).

[46] A waste byproduct of the desalination process which contains a high concentration of salt (Cooley et al. 2013).

brine with treated wastewater to dilute the salinity, and discharges it a mile and a half offshore (City of Santa Barbara 2019). Discharging brine offshore is helpful in reducing the brine concentration, and lessening the harmful impacts to the local sea life (Einav 2007).

New methods are being introduced to reduce the overall sodium chloride concentration within brine. One such method includes converting brine to sodium hydroxide which depletes sodium chloride concentration within brine to 20% (Du et al. 2018). The depleted brine then undergoes dechlorination before being discharged, or recycled back into the conversion process (Du et al. 2018). Other by-products of the process include gases chlorine and hydrogen (Du et al. 2018). The sodium hydroxide can then be used to pretreat the seawater going into the desalination plant. This would change the acidity of the water, preventing fouling and tears to the reverse osmosis membranes (Chandler 2019). Fouling[47] can disrupt the desalination process, sometimes causing the overall operation to be shut down.

Reclaimed

The City currently uses recycled water for landscape irrigation at golf courses, parks, homeowner associations, retirement homes, schools, and the Santa Barbara Zoo (City of Santa Barbara 2020). Recycled water utilizes treated wastewater already within the water distribution system. The City currently does not use recycled water to supplement the potable water supply. Recycled water can be used through indirect potable reuse. Indirect potable reuse injects recycled water into the groundwater aquifer so it can spend time within an environmental buffer before being reincorporated into drinking water (Pottinger 2016). In 2014, California established rules for indirect potable reuse that provided regulations for the treatment process and how long treated water must remain in the environmental buffer (WateReuse 2020). According to the South Coast[48] agencies, over 11 million gallons of wastewater is treated and discharged in the ocean between Goleta, Santa Barbara, Carpinteria, and Montecito each day (Staff 2017). The South Coast agencies estimate that the City has a 7,000 AFY recycled water potential. A Carollo Engineer study[49] estimated the cost for produced recycled potable blended water to be $600 per AF (City of Santa Barbara Water Resources Division 2011).

Proponents of recycled water often describe it as a drought resistance water source. This is true as recycled water is not dependent on precipitation. Yet, during times of droughts recycled water has seen a decline in production due to conservation efforts (McCann & Chappelle 2019). The City encourages residents to transition to high efficiency water use washing machines and drought tolerant landscapes by offering incentives such as rebates (City of Santa Barbara 2020). The City's

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[47] The accumulation of deposited materials on the osmosis membrane surface that restrict flow through the membrane pores (SAMCO 2018).

[48] The South Coast refers to: Goleta, Santa Barbara, Carpinteria, and Montecito.

[49] The Carallo Engineer study was on the feasibility of a recycled water filter rehabilitation project that further reduced mineral content in the current recycle water supply without the use of blending (City of Santa Barbara Water Resources Division 2011).

future conservation efforts could impact future recycled water production as there would be less wastewater in the system. The affordability of recycled water can allow the City to better respond to water scarcity in the future.

The State Water Board is currently establishing a framework of regulations for direct potable reuse. Direct potable reuse skips the environmental buffer step and goes directly into becoming drinking water (Pottinger 2016). The framework is establishing guidelines for the treatment plants and risk management approaches to direct potable reuse. The State Water Board plans on releasing standards for direct potable reuse by December 31, 2023 (State Water Resources Control Board 2019). The advantage of direct potable reuse is the ability to quickly get recycled water into the drinking water system. Concerns over direct potable reuse largely stem from concerns about contaminants remaining in the treated water (Naik 2014).

State Water Project and Water Purchases

The City has adapted their yearly water portfolios to incorporate a range of proportions of their total State Water Project allocation. This variability is driven by numerous management and climatic factors, and not likely to stabilize considering climate change. California Department of Water Resources (DWR) predicts substantial decreases in SWP water availability by 2050 (Flores 2015).

The Department of Water Resources and their Climate Change Technical Advisory Group conducted a downscaled climate change impact analysis of California streamflow, largely concentrating on the Sacramento and San Joaquin River Basins, incorporating 20 climate models under both Representative Concentrations Pathways (RCP) 4.5 and 8.5 (Department of Water Resources 2018). This analysis also accounted for an extreme drought scenario under RCP 8.5. to gain a better understanding of how shifts in precipitation, temperature and overall seasonality may influence the amount and timing of SWP deliveries throughout the system. According to the State Water Project Final Delivery Capability Report 2017, long-term average deliveries are estimated to decrease up to 62% and on average decrease 29% across all models under RCP 8.5 (Department of Water Resources 2018).

Santa Barbara relied relatively more heavily on State Water Project deliveries from 2014 to 2018 during the latest drought and following recovery. In 2018 for example, State Water Project deliveries contributed 44% of the City’s water. Understanding that State Water Project deliveries have historically been variable and deliveries are likely to decrease throughout the system, the City’s reliance on State Water Project during future drought years may be limited.

4.4 City of Santa Barbara Demand

Considering increased variability of discharge in the upper SYR watershed, and therefore inflows to Gibraltar Reservoir and Lake Cachuma, the City must evaluate to what extent changes in local water supply jeopardize future demand. Such risk can be diminished through enhanced resilience within the City's already diverse water supply portfolio. The current City water demand projections, illustrated in Figure 42, work to anticipate water use rebound after the latest drought, while also considering new drought efficiency infrastructure (Corey 2020). The projections also account for population growth characterized in the 2011 General Plan, the City's conservation program, enhanced water use metering and indicates that the City's will demand ~13,000 AFY by 2050 (Corey 2020).

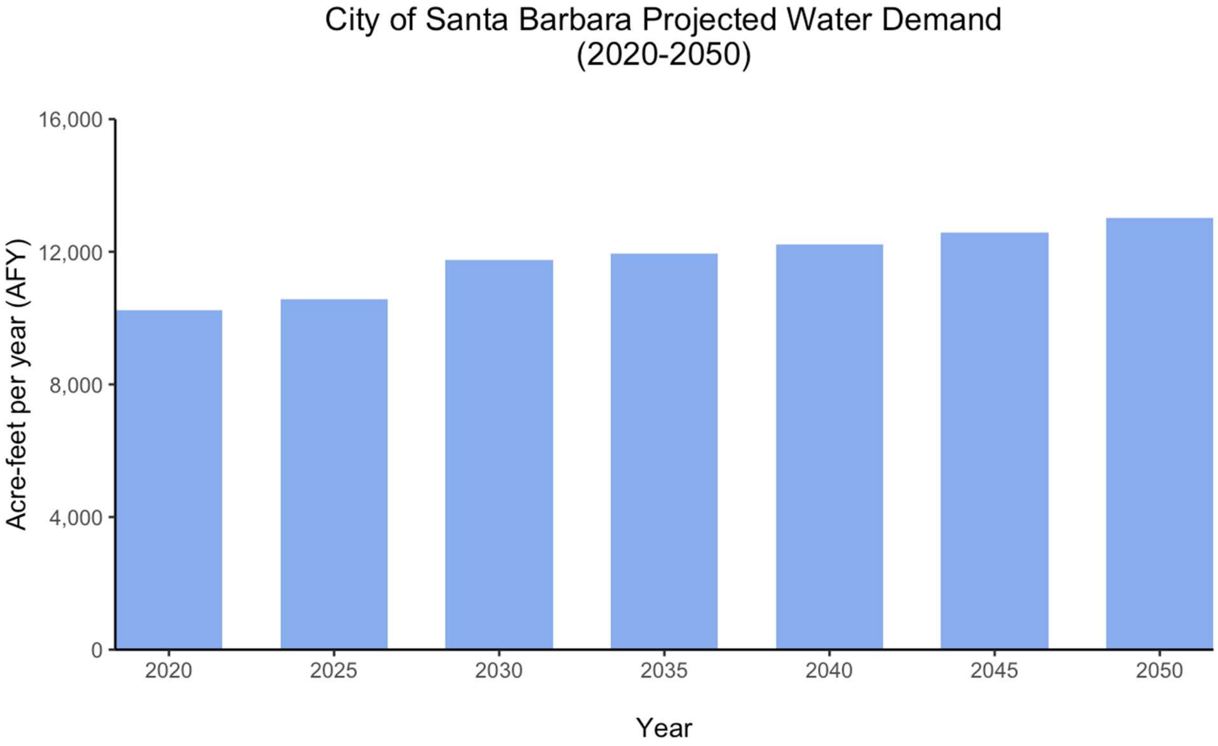

Figure 42. Projected water demand for the City of Santa Barbara by year from 2020 to 2050. Data sources: Dakota Corey, City of Santa Barbara Public Works. Accessed February 2019.

The relative difference between the projected streamflow in the SYR watershed for each climate model and estimated variability in reservoir inflows may be used by the City to better understand future local water supply variations contrasted by predicted demand. The difference between these variations and yearly demand scenarios to the year 2050 will act as the anticipated "water gaps" that the City may account for. Understanding the potential severity of the water gap will enable the City to adapt its water supply strategies to meet expected future demand.

4.5 Project Uncertainty

There are levels of uncertainty associated with using a hydrologic model to project future streamflow. Each stage of the project, including data measurement, model inputs, model calibration, and climate model projection, is associated with some uncertainty.

Resolution of Spatial Data

Input data required to run the SWAT model include a digital elevation model (DEM) and land use, soils, and stream network shapefiles. Each spatial data has its own resolution and the coarser the spatial scale and the lower the quality of data, the harder it is to accurately represent a relatively small area (Li et al. 2017). The DEM raster used to run the SWAT model has a resolution of 100 meters. The land use and soils shapefiles were obtained from the USGS Land Cover National Database and National Cooperative Soil Survey, respectively, and clipped to the upper SYR watershed. The resolution of the land use and soils shapefiles is 30 meters.

Santa Cruz Flow Measurements

Santa Cruz Creek watershed is relied upon in this analysis for ArcSWAT model calibration; however, flow measurements at the USGS Santa Cruz gauge have uncertainty. The Santa Cruz gauge is checked by USGS every 6 - 8 weeks, 8 - 10 times per year, or as needed for suspected maintenance issues (Ben Glass 2020). Rating curves are adjusted according to changes in channel morphology, as there is commonly sediment or vegetation build up or movement (Ben Glass 2020). There is no cable measurement system across the stream, hence, there is a higher range of uncertainty in measurements taken and extrapolated during high flows (Robinson 2020).

Representation of Upper Santa Ynez River Reservoir Levels

As described in Chapter 3, total upper Santa Ynez inflow to Cachuma Reservoir is estimated using approximations of Santa Cruz Creek contributions to Cachuma Reservoir.

Historical Precipitation and Temperature Measurements

The model used daily precipitation measured at Lake Cachuma from 1980 to 2018. The County of Santa Barbara records rainfall on a daily basis at the outlet of Lake Cachuma using automated sensors (Santa Barbara County). The model included daily temperature recordings for the historical time period from Lake Cachuma and Gibraltar. NOAA measures daily maximum and minimum temperature through the Global Historical Climatology Network (GHCN-Daily; Menne et al. 2018).

The model used historical precipitation measured at the Lake Cachuma precipitation station from 1980 to 2018 for the upper watershed. Precipitation can be different throughout the SYR watershed due to the orographic effects in the Santa Ynez Mountains and San Rafael Mountains. However, because the model was specifically calibrated for a sub-basin near Lake Cachuma, it seems acceptable to have used only historical precipitation recorded at Lake Cachuma as the precipitation input for the upper part of the watershed .

SWAT Model

The initial SWAT model run was over-predicting historical discharge, which is why calibration of the model via the altering of hydrologic, atmospheric, and soils parameters was required. Parameters for the model were adjusted using studies conducted in similar watersheds. These studies provided ranges in hydrologic, atmospheric, and soils parameters for watersheds similar to the Santa Ynez. However, there is uncertainty associated with parameter adjustment, as studies were not done specifically in this watershed to determine the most accurate parameter adjustments.

Because there is uncertainty associated with model parameter adjustment during calibration, future work could include conducting a sensitivity analysis within the SWAT Calibration and Uncertainty Program (SWAT-CUP). A sensitivity analysis could help determine which of the model parameters have the most influence on simulated streamflow within this particular watershed. Running a sensitivity analysis would require multiple model iterations with a range of simulations within each iteration. There are two types of sensitivity analyses: one-at-a-time (OAT), in which the modeler holds all parameters constant except one to identify that parameter's effect on model outputs, and all-at-a-time (AAT), also known as global sensitivity, in which all parameters are changing at the same time (Abbaspour et al. 2016). AAT sensitivity analysis requires many more simulations than OAT, ranging from 500 to 1000 model simulations.

The SWAT model does not account for orographic effects on precipitation, which can be substantial within this watershed. Again, this is acceptable for the purposes of the model because the model was specifically calibrated for the sub-basin near Lake Cachuma (County of Santa Barbara). Future work could include creating elevation bands within the ArcSWAT interface when running the model for streamflow projections.

Only one SWAT simulation was run per climate model to obtain projected streamflow. Future work would include running multiple model simulations for each climate model projected temperature and precipitation values to obtain a range in potential projected streamflow for each climate model for the years leading up to 2050.

Climate Change Projections

There are three main uncertainties with climate change projections: the first is uncertainty in the future concentration of greenhouse gases in the atmosphere, the second is uncertainty regarding future climate changes in response to anthropogenic forcings, and the third is model uncertainty (Hawkins and Sutton 2010).

Using Representative Concentration Pathways (RCPs) is a common way of addressing the uncertainty in the future concentration of greenhouse gases in the atmosphere (van Vuuren et al. 2011). These RCPs capture potential future emissions scenarios. The project uses only RCP 8.5, the high emissions scenario, because the City wants to plan conservatively for the future. Additionally, using RCP 8.5 maintains consistency with the City's other planning documents. To account for uncertainties in how climate change will impact local conditions in the future, five different climate change models that simulate a wide range of possible futures for the region were selected. Model uncertainty occurs when individual climate models produce different future climate outcomes in response to the same radiative forcings[50] (Hawkins and Sutton 2010). Given the scope of the project and time limitations, model uncertainty is not addressed in this work. One way to address this form of uncertainty in future work is to run multiple simulations for each climate model.

Chapter 6. Recommendations

Recommendation 1: Reservoir Sedimentation

Sedimentation in both Cachuma and Gibraltar reservoirs requires ongoing discussion and actions between the City, the Cachuma Operations and Maintenance Board, and all other users. As Gibraltar reservoir has effectively reached the end of its lifetime due to nearly complete sedimentation; Cachuma Reservoir may experience increased sedimentation relative to historical rates. Moreover, climate change impacts such as increased frequency and intensity of wildfire and more intense precipitation events could also increase sedimentation. Sedimentation impacts the amount of water that can be stored and therefore potential mitigation strategies for Cachuma reservoir should be decided upon before sedimentation begins to inhibit total water stored.

Recommendation 2: Data Collection

Streamflow throughout the SYR watershed is highly variable, dependent on the amount of precipitation occurring within a rainy season in a given year. Increasing the number of stream discharge gauges in appropriate locations could help the City more precisely model future conditions in the watershed. With more streamflow data, the relationship between streamflow and watershed reservoir storage could be better understood.

Recommendation 3: Streamflow Seasonality

Future changes in the timing of streamflow due to climate change will impact water supply. This analysis suggests that the seasonality of streamflow may shift as the climate changes. Much of the research on this topic has been completed for snow-dominated watersheds. Understanding how climate change may impact the timing of streamflow in the rain-dominated SYR watershed and how the consequences of these changes may affect water supply will be important for future planning efforts. The implications of changes to overall watershed hydrology under shifting seasonality could incentivize future modeling efforts.

Recommendation 4: Conservative Planning

The City's water supply planning should remain conservative. As this analysis indicates, while

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[50] Radiative forcing is the difference between the heat absorbed by the earth and energy radiated back to space.

extreme scenarios such as the extended drought are not likely, their consequences could be drastic. If the City continues to plan for a water supply that is increasingly variable, and perhaps limited out to 2050, demand will be more readily met. The City has already initiated such conservative and responsible planning, evidenced by the inclusion of climate change discussion and quantification in their long-term planning efforts. As the SYR watershed supply is depended upon by multiple other municipalities and private users, cohesive and conservative climate change planning would be beneficial, and the City would be a clear leader in these efforts.

Appendix

Appendix 1. External Project Data Sources

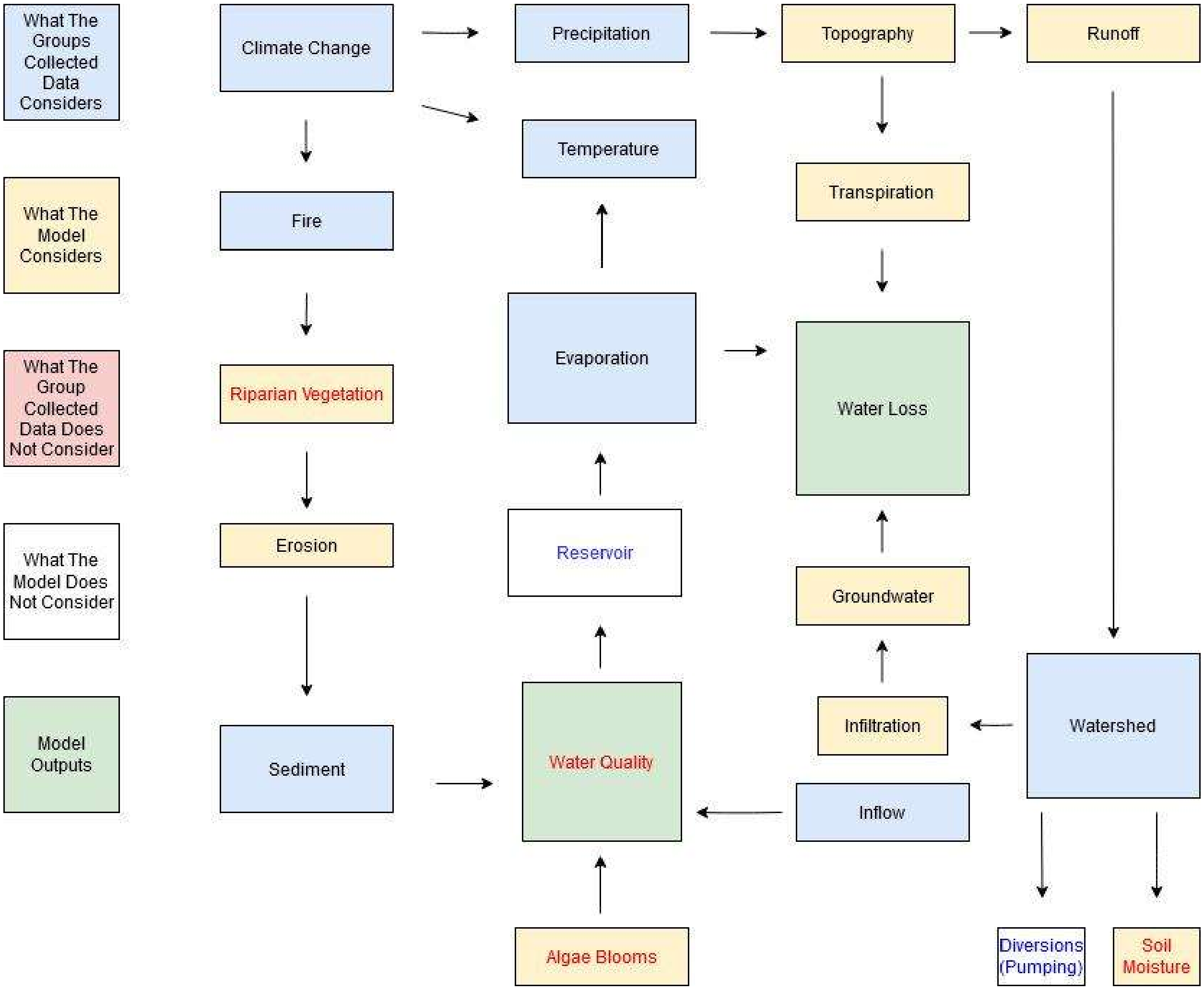
Reservoir/Climatic Parameter	Data Explanation	Sources
Cachuma	Daily Rainfall Record	County of Santa Barbara
Cachuma	Cachuma Daily Operations Database: Daily Storage, Water Levels, Inflows, and Elevation vs. Capacity 1999 to 2018	Cachuma Operations and Maintenance Board (COMB)
Cachuma	Evaporation, Precipitation, Maximum & Minimum Historical Temperatures	National Oceanic and Atmospheric Administration (NOAA)
Cachuma	Bathymetric Capacity Data	COMB
Cachuma	Monitored Capacity Data	County of Santa Barbara
Gibraltar	Bathymetric Capacity Data	City of Santa Barbara
Gibraltar	Monitored Capacity Data	County of Santa Barbara
Gibraltar	Daily Rainfall Record	County of Santa Barbara

Gibraltar	End of Month Storage Volume 1991 - 2019	City of Santa Barbara
Gibraltar	Monthly Inflows 1920 - 1990 (projected from 1990 - 2002)	City of Santa Barbara
Gibraltar	Daily Inflows 1990 - 2019	City of Santa Barbara
Gibraltar	Historical Climate Data	NOAA
Gibraltar	Historical Climate Data (Temperature)	NOAA
Groundwater	Water Level Recordings for the City's Multiple Groundwater Storage Units	United States Geological Survey (USGS)
Fire	Major Wildfires Acreage Burned in SB 1955 - 2016 & Recorded Fires/Acreage Burned in Santa Ynez watershed and upper Santa Ynez watershed from 1913-2018	California Department of Forestry and Fire Protection's Fire and Resource Assessment Program (FRAP)
Climate Projections	Maximum Temperature Projections for Lake Cachuma	Cal-Adapt
Climate Projections	Minimum Temperature Projections for Lake Cachuma	Cal-Adapt
Climate Projections	Precipitation Projections for Lake Cachuma	Cal-Adapt

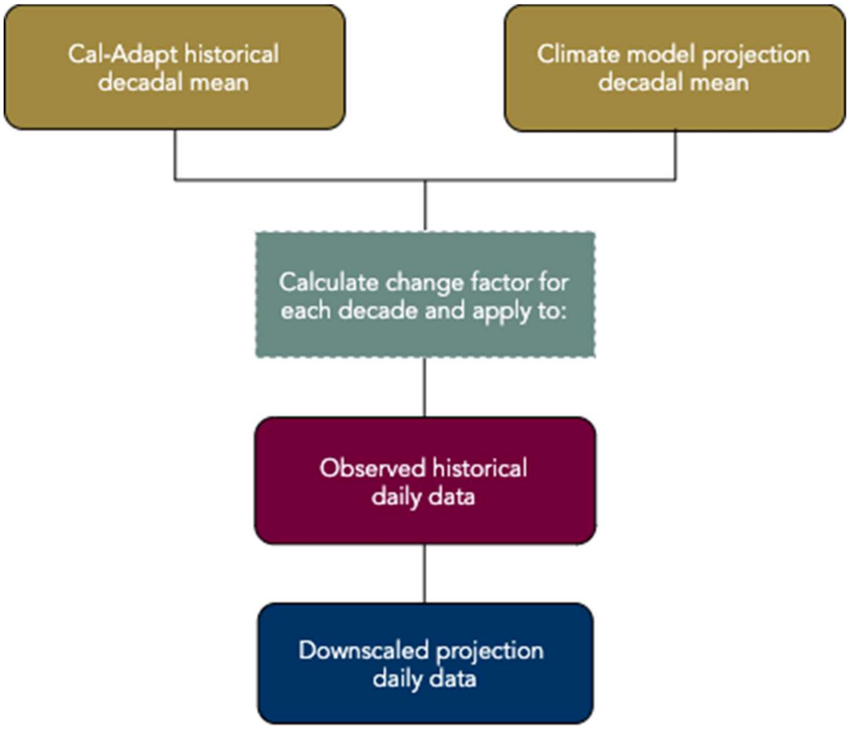
Climate Projections	Maximum Temperature Projections for Gibraltar	Cal-Adapt
Climate Projections	Minimum Temperature Projections for Gibraltar	Cal-Adapt
Climate Projections	Precipitation Projections for Gibraltar	Cal-Adapt
Climate Projections	Minimum Temperature, Maximum Temperature, and Precipitation Projections for Early Century Drought Lake Cachuma 2023 - 2042	Cal-Adapt
Climate Projections	Minimum Temperature, Maximum Temperature, and Precipitation Projections for Early Century Drought for Gibraltar 2023 - 2042	Cal-Adapt
Climate Projections	Minimum Temperature, Maximum Temperature, and Precipitation Projections for Late Century Drought Lake Cachuma, 2051 - 2070	Cal-Adapt
Climate Projections	Minimum Temperature, Maximum Temperature, and Precipitation Projections for Early Century Drought for Gibraltar, 2051 - 2070	Cal-Adapt
Water Production	City of Santa Barbara Water Use in Gallons Per Capita per Day, w/ and w/o blend, 2010 - 2019	City of Santa Barbara
Water Production	2004 - 2018 City of Santa Barbara Water Supply Sources	City of Santa Barbara

Water Consumption	2018 (Calendar Year) City of Santa Barbara Metered Water Sales By Class	City of Santa Barbara
Streamflow	Daily Mean Discharge at Santa Cruz Creek Gauge 11124500	USGS

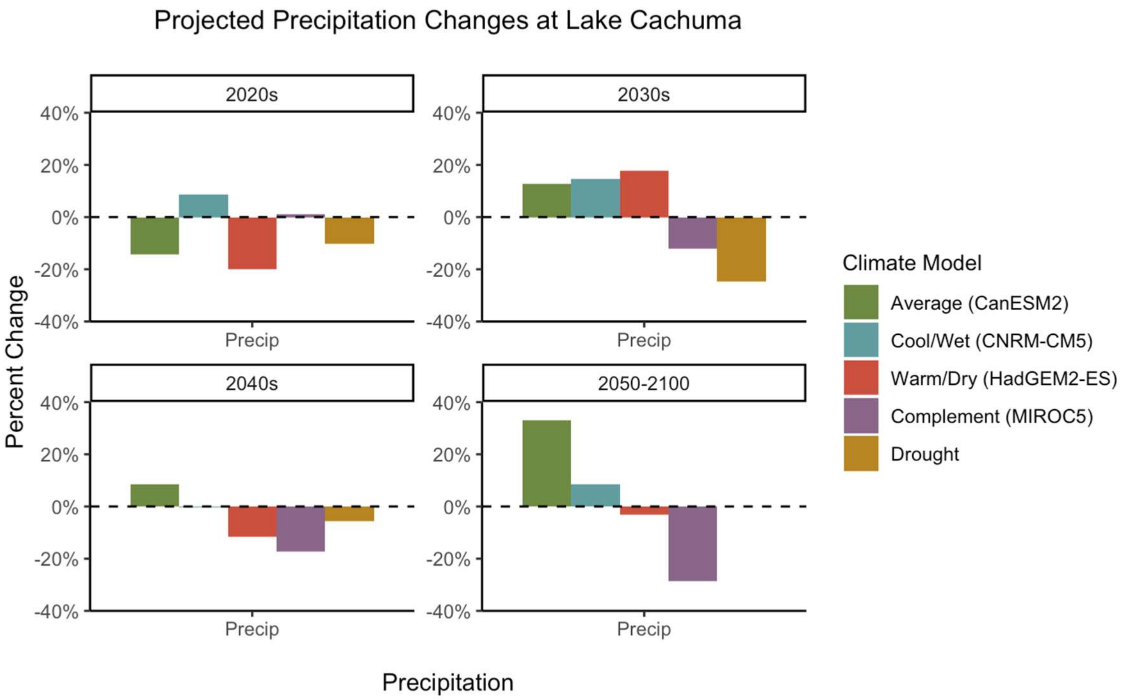
Appendix 2. Conceptual Model

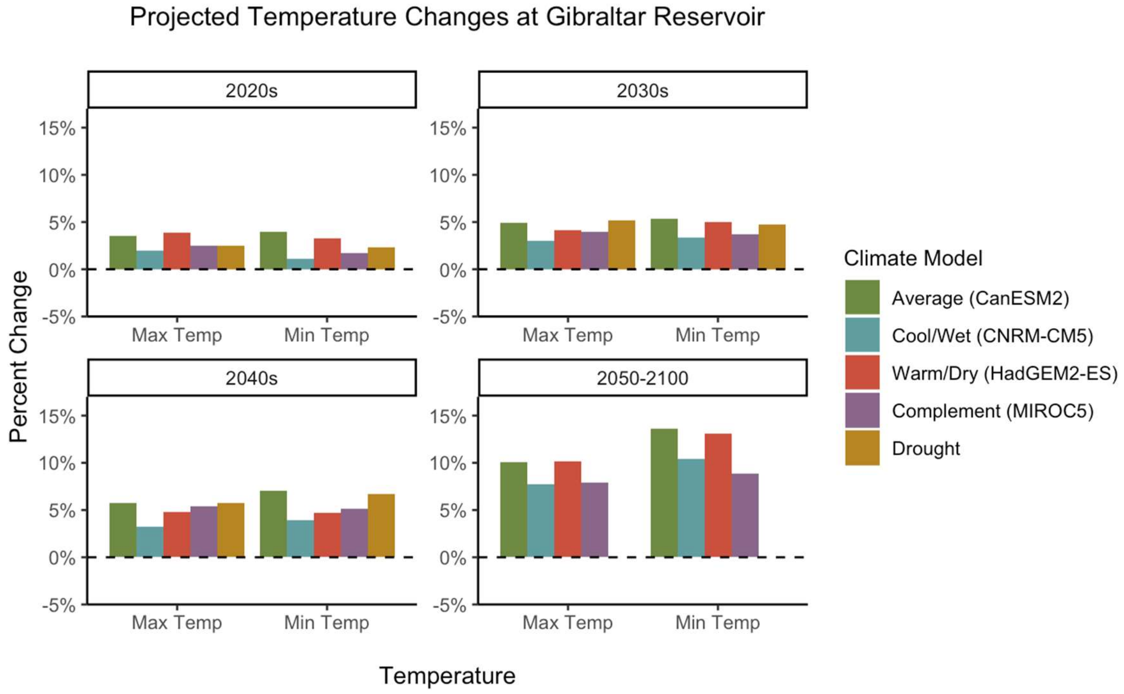


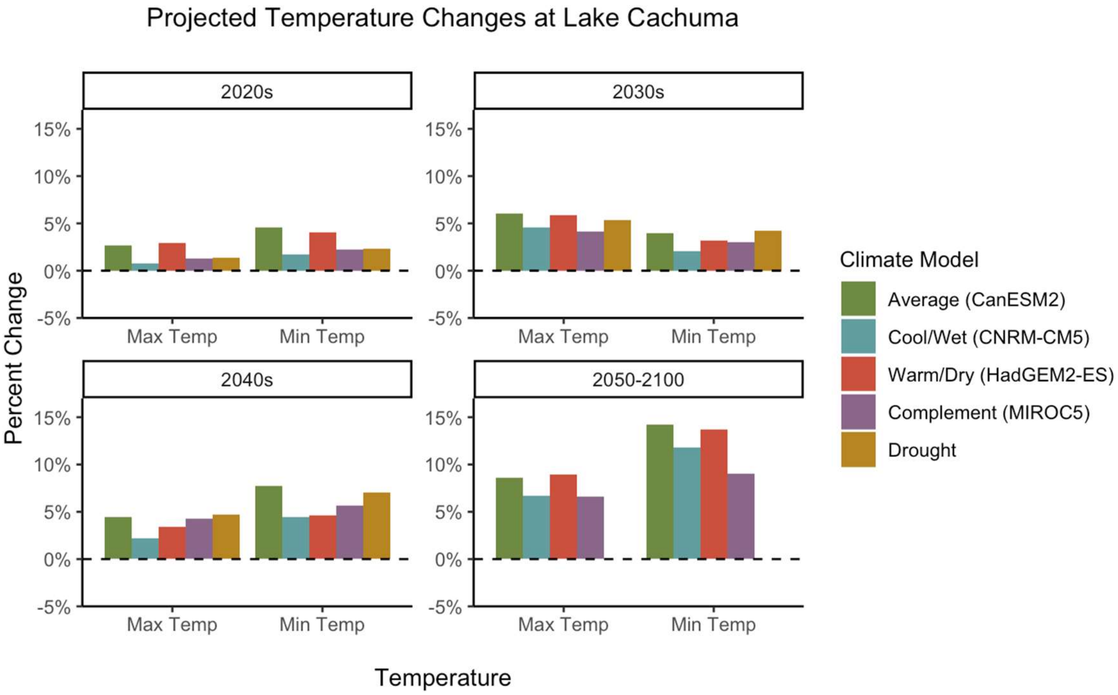
Appendix 3. Statistical Downscaling Flow Chart: Delta Change Method



Appendix 4. Projected Changes in Precipitation and Temperature






Projected Temperature Changes at Lake Cachuma
2020s
2030s
2040s
2050-2100
15%
10%
5%
0%
-5%
Max Temp
Min Temp
Percent Change
Temperature
Climate Model
Average (CanESM2)
Cool/Wet (CNRM-CM5)
Warm/Dry (HadGEM2-ES)
Complement (MIROC5)
Drought

Appendix 5. ArcSWAT Water Balance Equation

SWAT incorporates the following water balance equation to model the hydrologic cycle of the watershed (Saharia 2018).

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})$$

The variables for the water balance equation are as follows: t is time in days, SW_t is the ending water content in the soil for the modeling period in millimeters (mm), SW_0 is the beginning water content in the soil of the modeling period (mm), R_{day} is total precipitation (mm) per day in the modeling period, Q_{surf} is the total surface runoff (mm) per day in the modeling period, E_a total evapotranspiration (mm) per day in the modeling period, W_{seep} is the total infiltration (mm) per day in the modeling period, and Q_{gw} is the total return flow (mm) per day in the modeling period (Saharia 2018).

Evapotranspiration includes the transpiration of water from vegetation and the evaporation of water from the soil (Wang et al. 2006). Estimating evapotranspiration can be done by generating the potential evapotranspiration. Potential evapotranspiration (PET) is the potential evaporation and transpiration within a vegetated area that can occur as long as water is available. SWAT accounts for PET by utilizing three different methods: the Hargeaves, Priestley-Taylor, and the Penman-Monteith equations. SWAT defines Actual Evapotranspiration (AET) as the water that is actually removed from the watershed (Wang et al. 2006). SWAT incorporates a similar technique with the Ritchie[51] method to calculate the maximum transpiration and evaporation values. SWAT calculates AET by estimating PET using the Hargeaves, Priestley-Taylor, or Penman-Monteith methods.

The following is how SWAT calculates evaporation from rainfall, transpiration from plants, and soil evaporation for AET. If PET is less than the available water in the canopy than SWAT employs the following formula:

$$R_{INT(f)} = R_{INT(i)} - E_{can}$$

where $R_{INT(f)}$ is the final amount of water in (mm) held in the canopy for a single day, $R_{INT(i)}$ is the initial amount of water in (mm) held in the canopy for a single day, and E_{can} is the amount of evaporation from water in (mm) within a canopy for a single day (Neitsch et al. 2011). If PET is greater than the amount of water held in the canopy than SWAT incorporates the formula below (Neitsch et al. 2011).

$$R_{INT(f)} = 0$$

---

[51] Evaporation from soil is calculated by using the constant supply of energy to the surface and the water controlling properties of water in the soil while transpiration is calculated using the area leaf index (Ritchie 1972).

SWAT calculates transpiration differently depending on the method used to determine PET. For the Hargreaves and Priestley-Taylor method SWAT calculates transpiration by using two formulas based on the leaf area index. If the leaf area index is between 0 and three then the formula below is used (Neitsch et al. 2011).

$$E_t = \frac{E'_o * LAI}{3.0}$$

E_t is the maximum transpiration (mm) that can occur in a single day, E'_o is the potential evapotranspiration of the water (mm) in the canopy, and LAI is the leaf area index (Neitsch et al. 2011). If the leaf area index is greater than 3 the following formula is used:

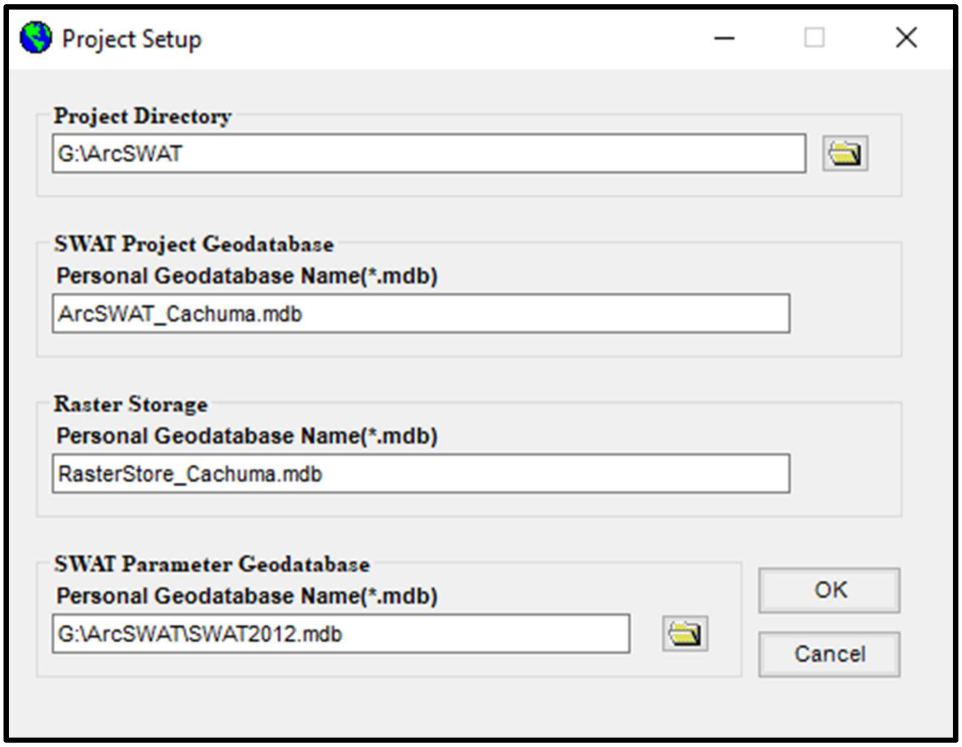
$$E_t = E'_o$$

The formulas above will calculate transpiration for a plant that is growing under ideal conditions (Neitsch et al. 2011). If SWAT used the Penman-Monteith method to estimate PET, then it will use the Penman-Monteith equation to estimate AET as it does for PET. SWAT also takes into account the soil heat flux, aerodynamic resistance, and canopy resistance when calculating AET. To calculate evaporation from soil SWAT takes into account shading from canopy which is reflected in the equation below:

$$E_s = E'_o * cov_{sol}$$

Where E_s is the maximum evaporation from soil for a single day in mm, E'_o is the potential evapotranspiration of the water within the canopy and cov_{sol} is the soil cover index (Neitsch et al. 2011). The soil cover index characterizes how many days of the year the soil is covered by biomass (Agriculture and Agri-Food Canada 2016).

Appendix 6. ArcSWAT Workflow



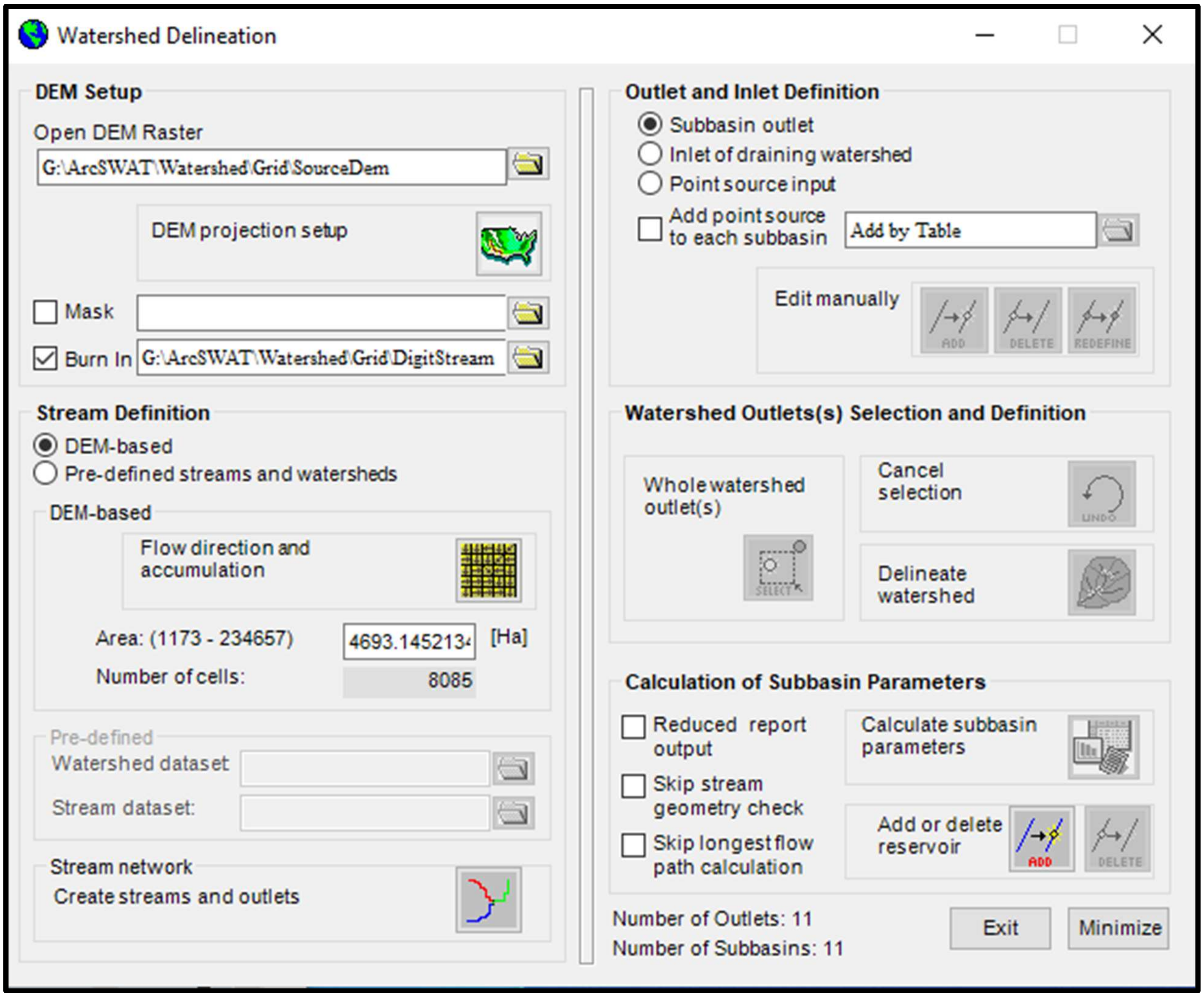
Project Directory
G:\ArcSWAT

SWAT Project Geodatabase
Personal Geodatabase Name(*.mdb)
ArcSWAT_Cachuma.mdb

Raster Storage
Personal Geodatabase Name(*.mdb)
RasterStore_Cachuma.mdb

SWAT Parameter Geodatabase
Personal Geodatabase Name(*.mdb)
G:\ArcSWAT\SWAT2012.mdb

1. Setting up a new SWAT project involves creating a new SWAT project directory. The file directory will be stored on the computer local disk (C:) or local network. Choosing a name for the project directory will auto-populate the name fields for the *SWAT Project Geodatabase*, *Raster Storage*, and *SWAT Parameter Geodatabase* (Merwade & Rajib 2018). After the project is created the *SWAT Project Geodatabase*, *Raster Storage*, and *SWAT Parameter Geodatabase* files will be found in the SWAT project directory.



Watershed Delineation

DEM Setup

Open DEM Raster: G:\ArcSWAT\Watershed\Grid\SourceDem

☐ Mask

☑ Burn In: G:\ArcSWAT\Watershed\Grid\DigitStream

Stream Definition

● DEM-based
○ Pre-defined streams and watersheds

Area: (1173 - 234657) 4693.145213 [Ha]

Number of cells: 8085

Outlet and Inlet Definition

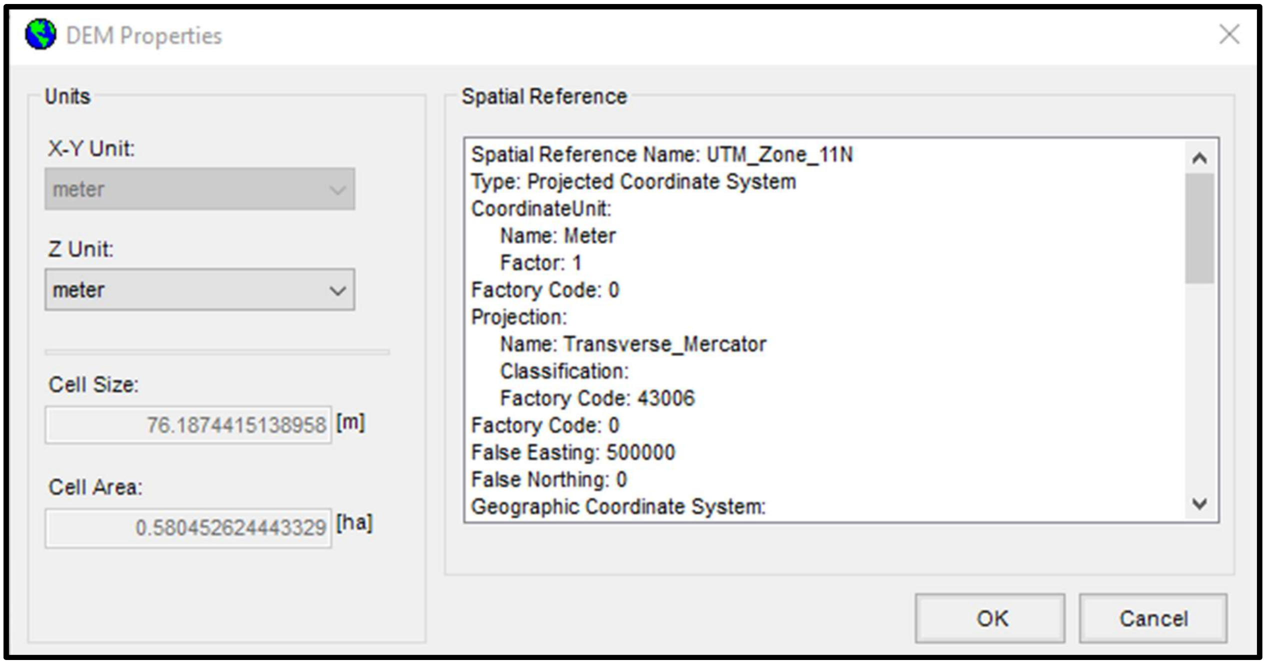
● Subbasin outlet
○ Inlet of draining watershed
○ Point source input
☐ Add point source to each subbasin: Add by Table

Calculation of Subbasin Parameters

☐ Reduced report output
☐ Skip stream geometry check
☐ Skip longest flow path calculation

Number of Outlets: 11
Number of Subbasins: 11

2. The watershed delineation begins by first selecting the DEM raster. By clicking the picture of the United States tab under the *DEM projection setup*, allows the user to verify the unit measurement which is shown in image three (Winchel et al. 2013). After choosing the DEM raster, the name will change to SourceDEM. Selecting *Burn In* allows the user to focus on a specific area of the watershed. To begin the stream definition check the *DEM-based* box as it delineates the watershed using the DEM raster that is uploaded into ArcSWAT. Click on the yellow square to adjust the *flow direction and accumulation*. Completing the *flow direction and accumulation* will auto-populate the area box. Clicking on the box with the red, blue, and green lines will define the stream network for the area that has been defined previously by the *flow direction and accumulation*. *Outlet and inlet definitions* allow the user to manually add inlets and outlets to the watershed stream network (Winchel et al. 2013). Selecting the whole watershed outlets(s) under the *Watershed Outlets(s) Selection and Definition* allows the user to manually select an outlet by using the select box (Merwade & Rajib 2018). Use the mouse to create a box around the outlet of interest. The outlet chosen will become a red dot which is reflected in image four.



X-Y Unit: meter

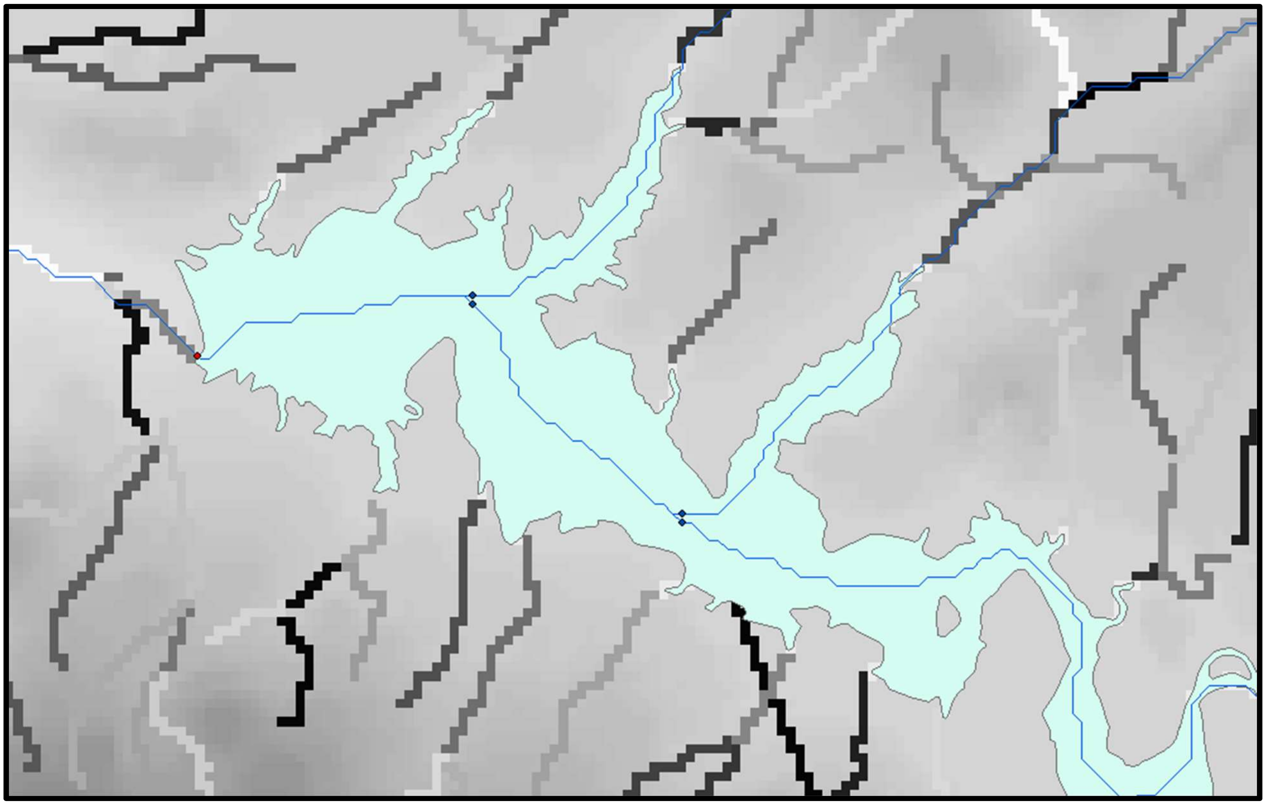
Z Unit: meter

Cell Size: 76.1874415138958 [m]

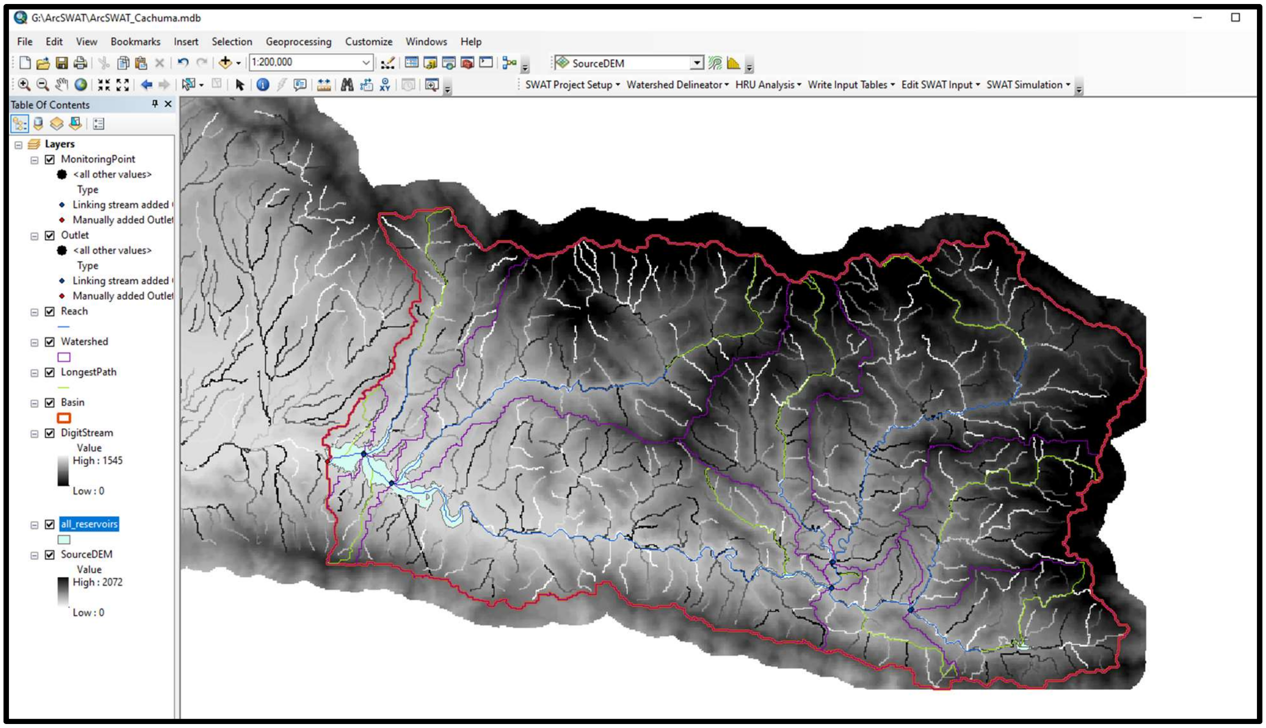
Cell Area: 0.580452624443329 [ha]

Spatial Reference Name: UTM_Zone_11N
Type: Projected Coordinate System
CoordinateUnit:
    Name: Meter
    Factor: 1
Factory Code: 0
Projection:
    Name: Transverse_Mercator
    Classification:
    Factory Code: 43006
Factory Code: 0
False Easting: 500000
False Northing: 0
Geographic Coordinate System:

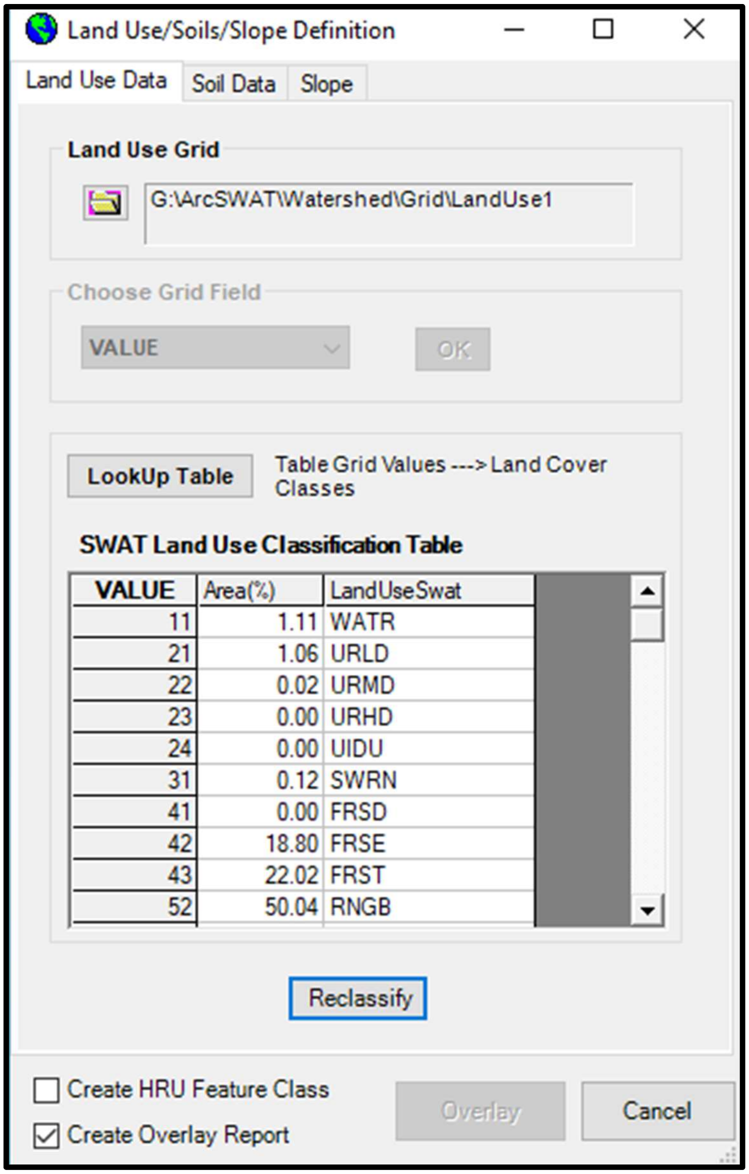
3. Dem Properties allow the user to define the units for the cell size and cell area.



4. The image shows how manually selecting an outlet in the watershed will be shown as a red dot. Once an outlet is selected the *Delineate watershed* button will become green signalling to the user ArcSWAT is now ready to delineate the watershed (Merwade & Rajib 2018).



5. After delineating the watershed a red line will appear around the watershed.



Land Use Grid: G:\ArcSWAT\Watershed\Grid\LandUse1

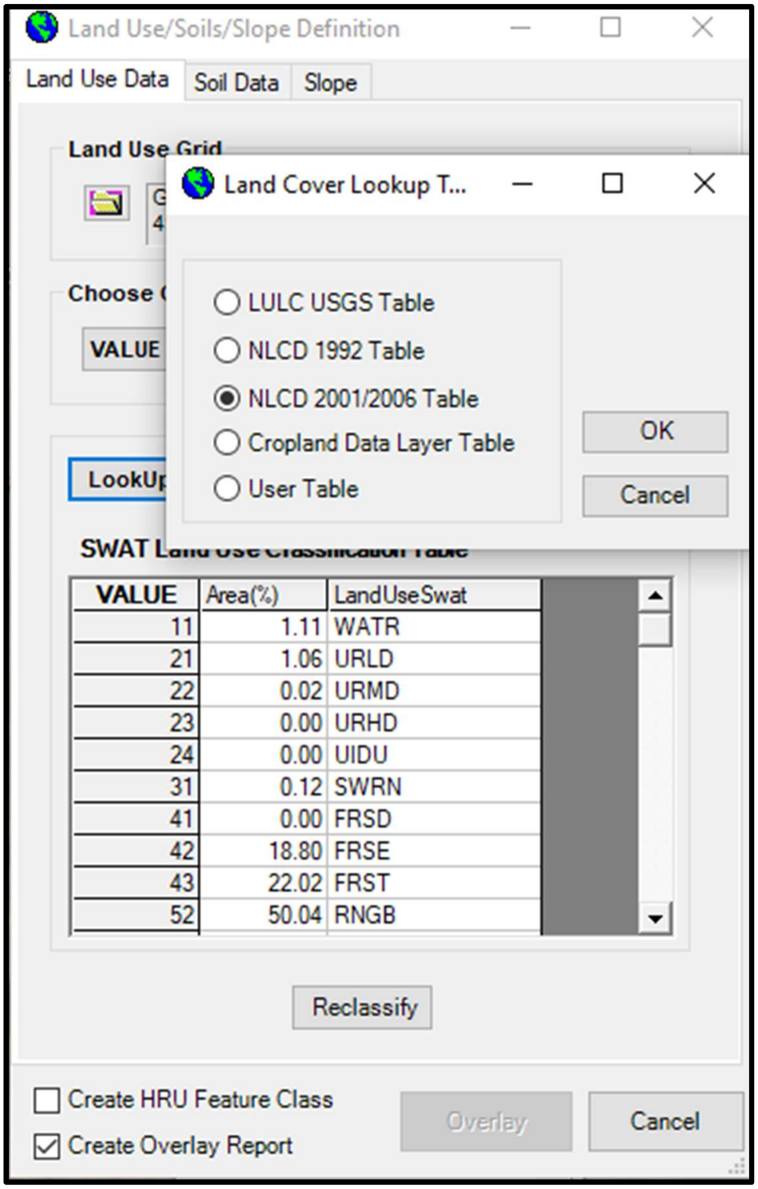
Choose Grid Field: VALUE

SWAT Land Use Classification Table

VALUE	Area(%)	LandUseSwat
11	1.11	WATR
21	1.06	URLD
22	0.02	URMD
23	0.00	URHD
24	0.00	UIDU
31	0.12	SWRN
41	0.00	FRSD
42	18.80	FRSE
43	22.02	FRST
52	50.04	RNGB

☐ Create HRU Feature Class
☑ Create Overlay Report

6. Clicking on the HRU Analysis tab on the ArcSWAT menu will bring up a drop down menu that includes *Land Use/Soil/Slope Definition*, *HRU Definition*, and *HRU Analysis Reports*. Clicking on the *Land Use/Soil/Slope Definition* will bring up the window shown above. Under *Land Use Grid* click on the file tab to select the land use data layer for the project. Clicking the file tab brings a Select Land Use Data box, check the *Select Land Use layer(s) from the map*. Once the land use data has been uploaded ArcSWAT will clip the land use layer(s) to the map (Merwade & Rajib 2018). Under *Choose Grid Field* select VALUE, and click the OK button.

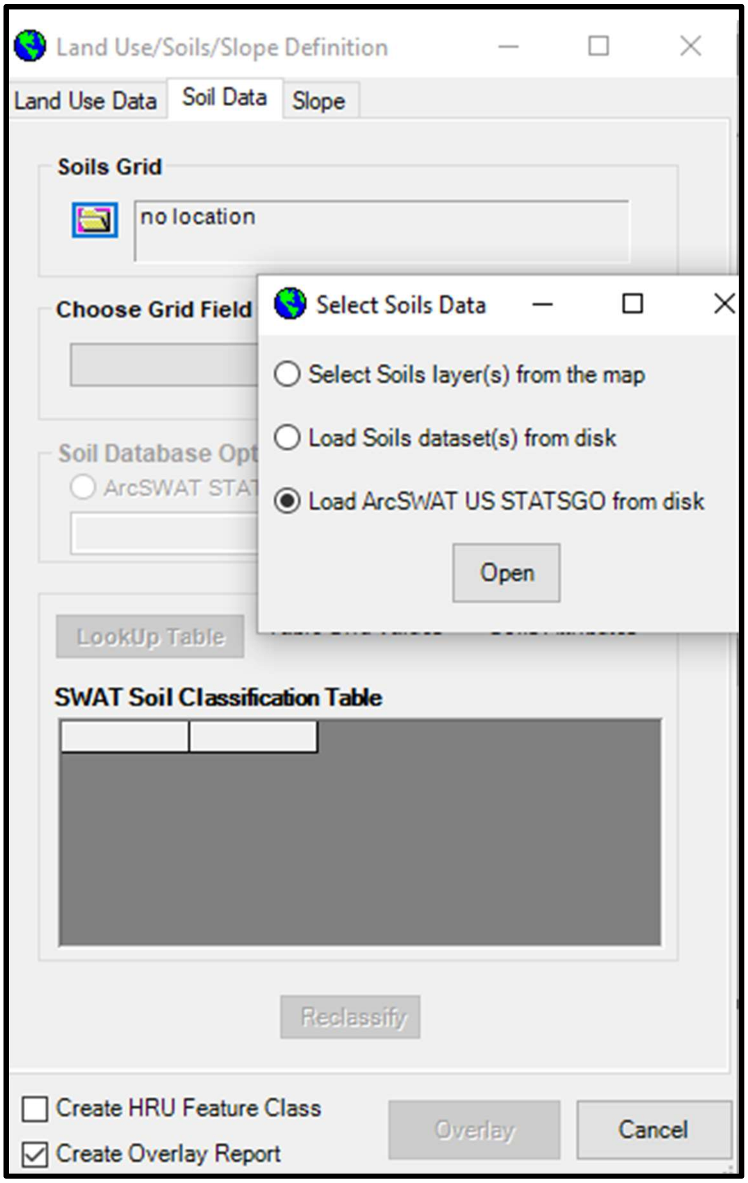


○ LULC USGS Table
○ NLCD 1992 Table
● NLCD 2001/2006 Table
○ Cropland Data Layer Table
○ User Table

VALUE	Area(%)	LandUseSwat
11	1.11	WATR
21	1.06	URLD
22	0.02	URMD
23	0.00	URHD
24	0.00	UIDU
31	0.12	SWRN
41	0.00	FRSD
42	18.80	FRSE
43	22.02	FRST
52	50.04	RNGB

☐ Create HRU Feature Class
☑ Create Overlay Report

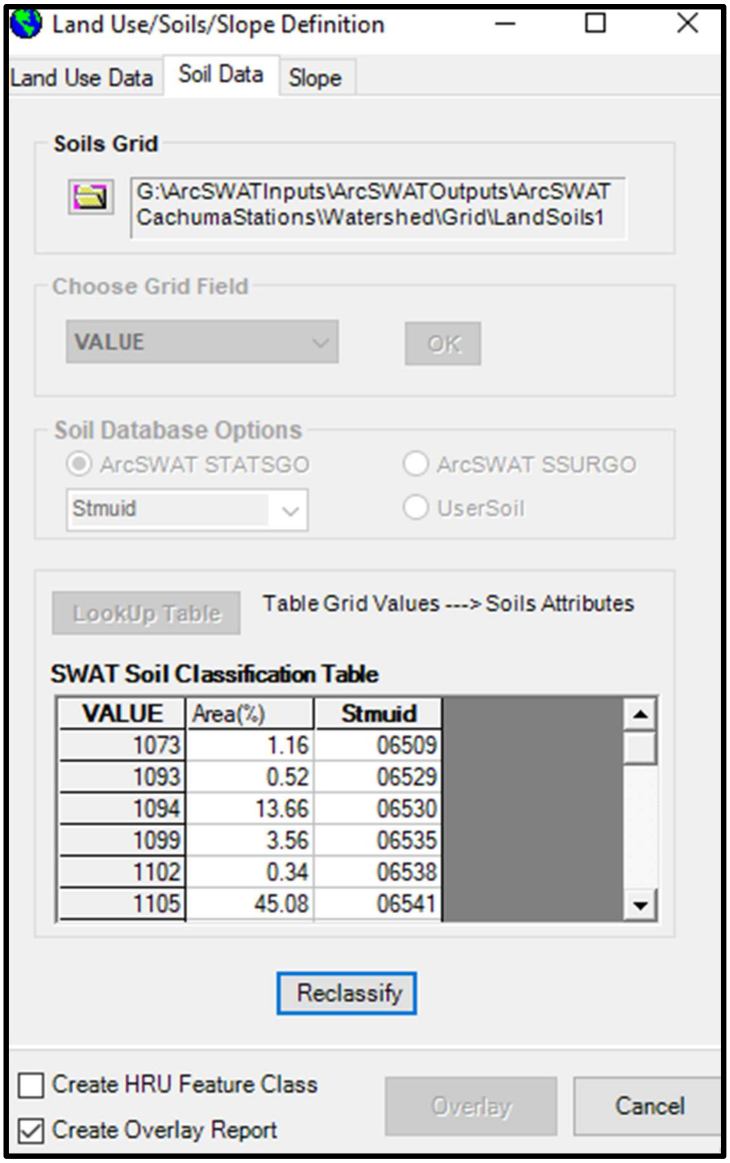
7. Clicking on the *LookUp Table* button will bring up the Land Cover Lookup Table selection box. Selecting the NLCD 2001/2006 Table will define the land use for the watershed. Click the *Reclassify* button to incorporate the land use data into the HRU (Merwade & Rajib 2018). Check the *Create Overlay Report* box.



○ Select Soils layer(s) from the map
○ Load Soils dataset(s) from disk
● Load ArcSWAT US STATSGO from disk

☐ Create HRU Feature Class
☑ Create Overlay Report

8. Click on the *Soil Data* tab to begin applying soil data to the HRU. This will prompt the Select Soils Data selection box to pop up. Click *Load ArcSWAT US STATSGO* from disk and click on the open button. Make sure to check the *Create Overlay Report* box.



Soils Grid

G:\ArcSWATInputs\ArcSWATOutputs\ArcSWAT CachumaStations\Watershed\Grid\LandSoils1

Choose Grid Field: VALUE

Soil Database Options

● ArcSWAT STATSGO ○ ArcSWAT SSURGO

Stmuid ○ UserSoil

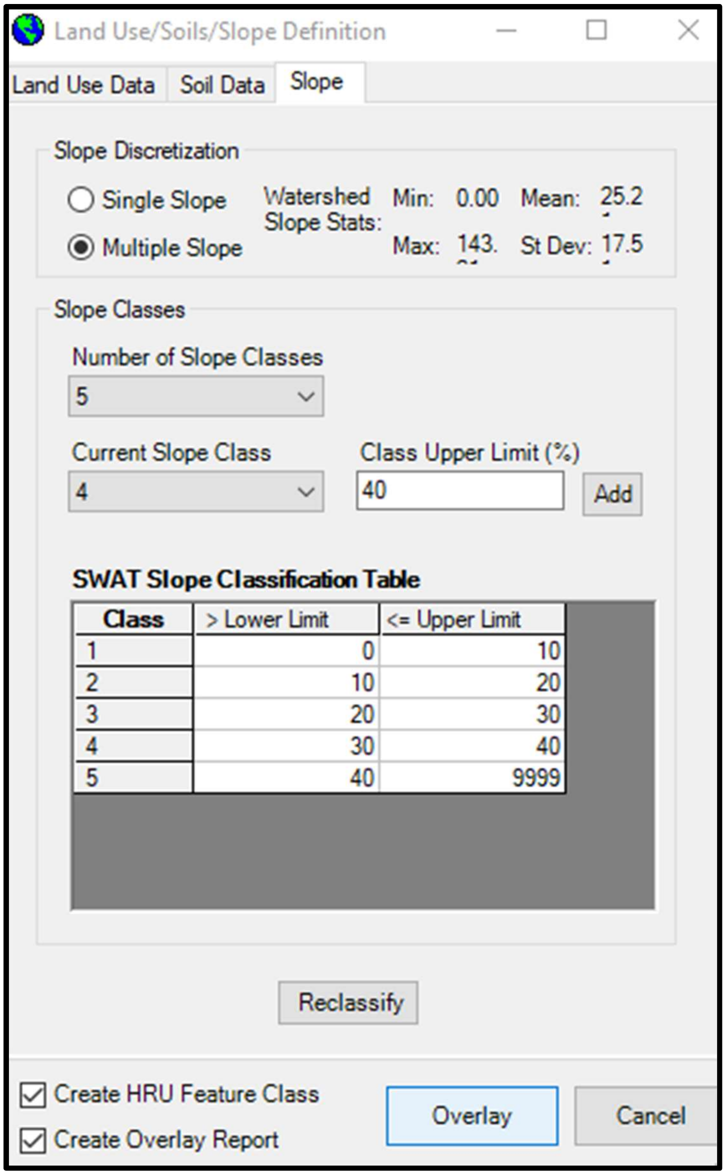
SWAT Soil Classification Table

VALUE	Area(%)	Stmuid
1073	1.16	06509
1093	0.52	06529
1094	13.66	06530
1099	3.56	06535
1102	0.34	06538
1105	45.08	06541

☐ Create HRU Feature Class

☑ Create Overlay Report

9. Under *Soils Grid* click on the folder button to load the soil data into ArcSWAT. Click on VALUE under the *Choose Grid Field* and hit the ok button. Select ArcSWAT STATSGO and choose Stmuid under the *Soil Database Options* and hit the *Reclassify* button.



Slope Discretization

○ Single Slope

● Multiple Slope

Watershed Slope Stats: Min: 0.00 Mean: 25.2 Max: 143. St Dev: 17.5

Slope Classes

Number of Slope Classes: 5

Current Slope Class: 4

Class Upper Limit (%): 40

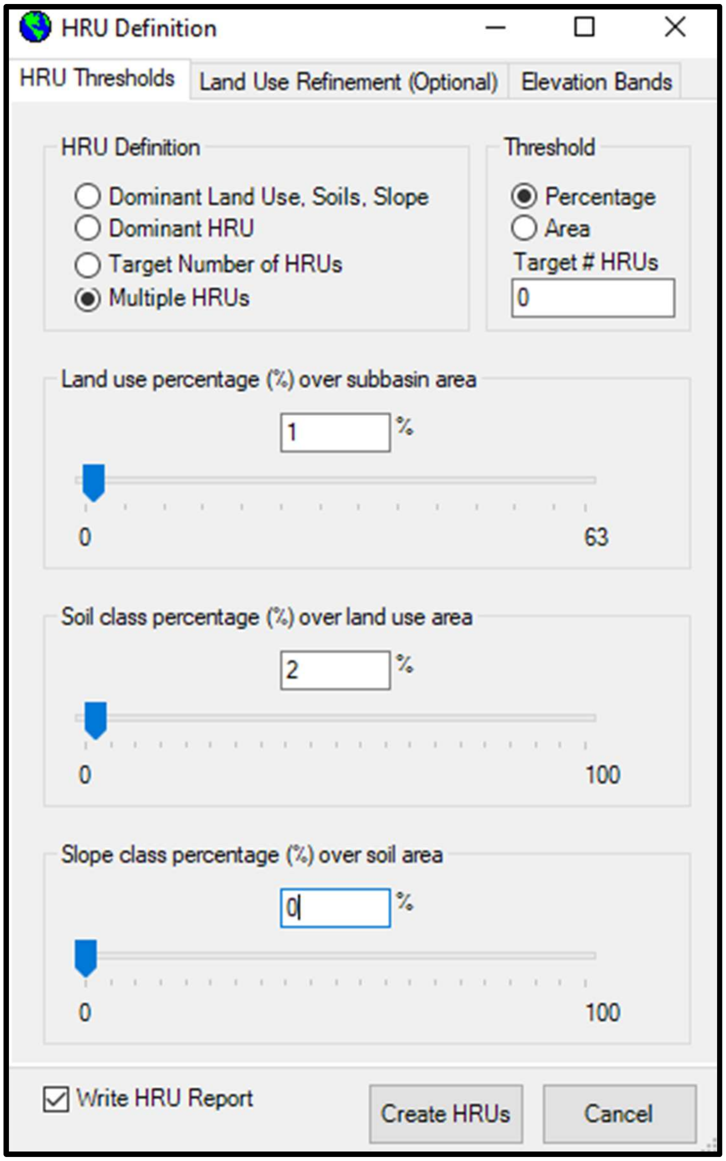
SWAT Slope Classification Table

Class	> Lower Limit	<= Upper Limit
1	0	10
2	10	20
3	20	30
4	30	40
5	40	9999

☑ Create HRU Feature Class

☑ Create Overlay Report

10. Click on the *Slope* tab to bring up the slope classification menu. Begin with *Slope Discretization* and choose Multiple Slope if the watershed is in a hilly area (Merwade & Rajib 2018). If the watershed has a flat terrain choose a single slope (Merwade & Rajib 2018). Under *Slope Classes* choose 5 for the *Number of Slope Classes*, and for the *Current Slope Class* begin with 0 and end with 40. Check the *Create HRU Feature Class* and hit the *Reclassify* button. Click on the *Overlay* button to conclude the HRU analysis process.



HRU Definition

○ Dominant Land Use, Soils, Slope
○ Dominant HRU
○ Target Number of HRUs
● Multiple HRUs

Threshold

● Percentage
○ Area

Target # HRUs: 0

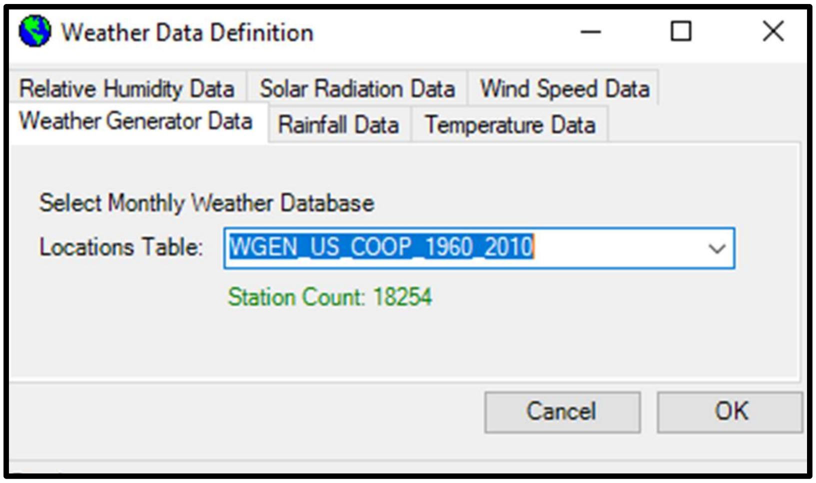
Land use percentage (%) over subbasin area: 1 %

Soil class percentage (%) over land use area: 2 %

Slope class percentage (%) over soil area: 0 %

☑ Write HRU Report

11. Click *HRU Analysis* in the ArcSWAT menu and click on *HRU Definition* to bring up the *HRU Definition* box. Begin with the *HRU Thresholds* tab under *HRU Definition* click on *Multiple HRUs* and under *Threshold* choose *Percentage*. Adjust the *Land Use Percentage (%) over subbasin area*, *Soil class percentage (%) over land use area*, and *Slope class percentage (%) over soil area* appropriately. Make sure to click the *Write HRU Report* box before clicking on the *Create HRUs* button.

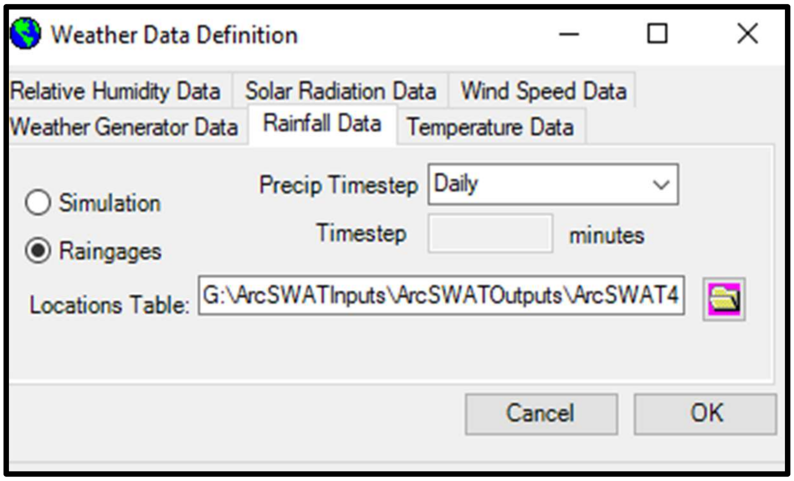


Select Monthly Weather Database

Locations Table: WGEN_US_COOP_1960_2010

Station Count: 18254

12. Click on the *Write Input Tables* and select *Weather Stations* to bring up the *Weather Data Definition* box. Begin with the *Weather Generator Tab* select WGEN_US_COOP_1960_2010 from the *Location Table* window.



○ Simulation

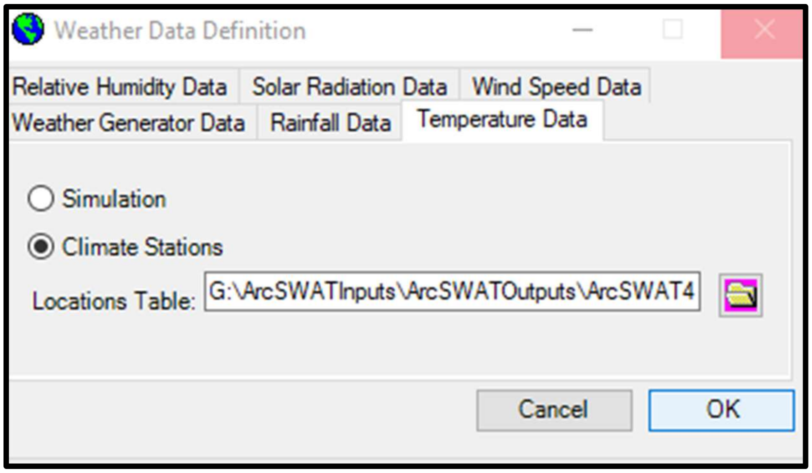
● Raingages

Precip Timestep: Daily

Timestep minutes

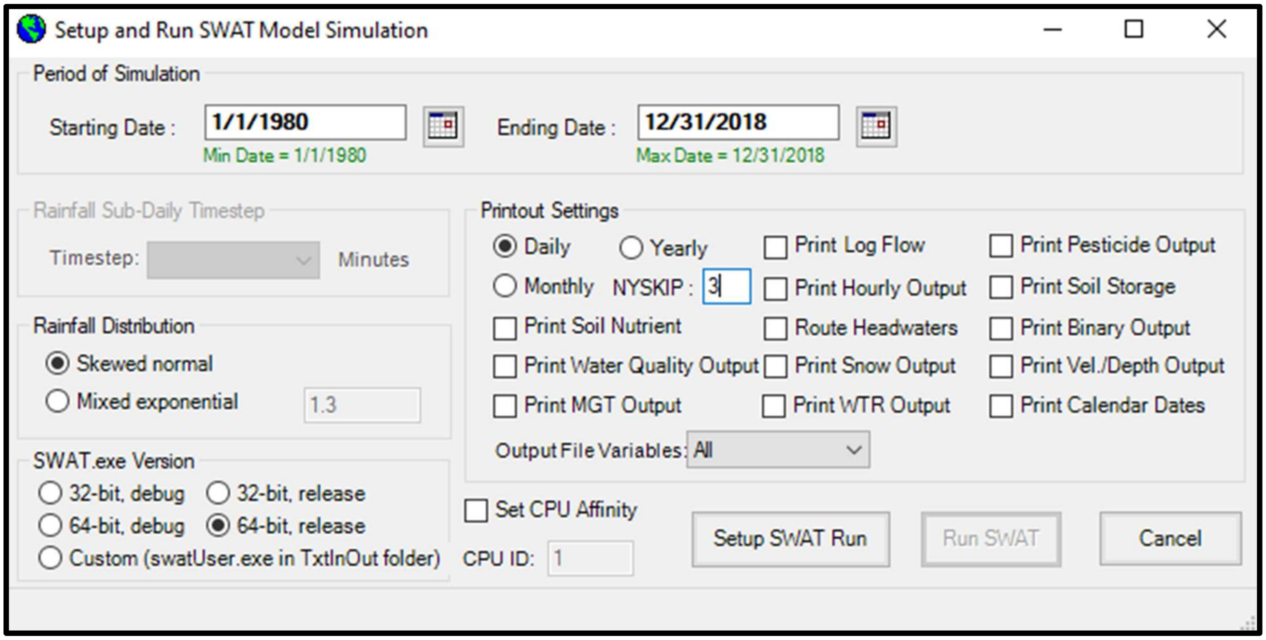
Locations Table: G:\ArcSWATInputs\ArcSWATOutputs\ArcSWAT4

13. Click the *Rainfall Data* tab to adjust the precipitation timestep. Adjust the precipitation timestep to be daily and click *Raingages* to use observed precipitation data (Merwade & Rajib 2018). Click the file icon to upload the observed precipitation pcp file.



○ Simulation
● Climate Stations
Locations Table: G:\ArcSWATInputs\ArcSWATOutputs\ArcSWAT4

14. Click on the *Temperature Data* tab and select *Climate Stations* to use observed temperature data (Merwade & Rajib 2018). Click on the file icon to upload the observed temperature tmp file.



Starting Date : 1/1/1980
Min Date = 1/1/1980
Ending Date : 12/31/2018
Max Date = 12/31/2018

Timestep: Minutes

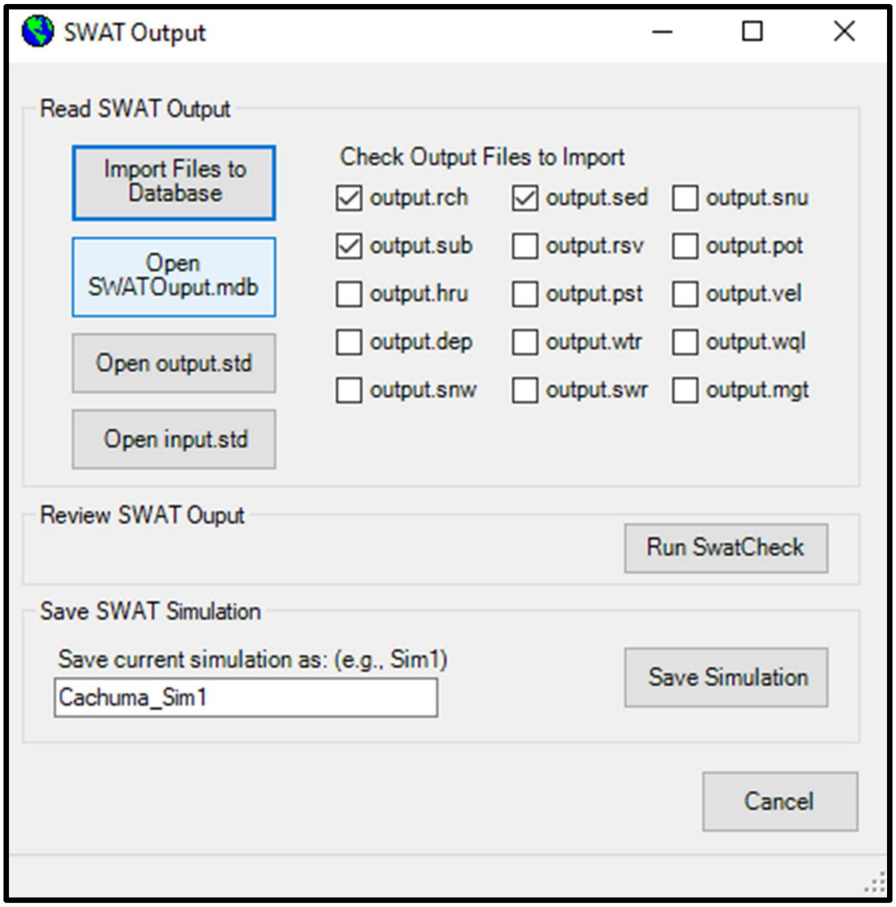
● Skewed normal
○ Mixed exponential 1.3

○ 32-bit, debug
○ 32-bit, release
○ 64-bit, debug
● 64-bit, release
○ Custom (swatUser.exe in TxtInOut folder)

● Daily
○ Yearly
○ Monthly
NYSKIP : 3
☐ Print Log Flow
☐ Print Pesticide Output
☐ Print Hourly Output
☐ Print Soil Storage
☐ Print Soil Nutrient
☐ Route Headwaters
☐ Print Binary Output
☐ Print Water Quality Output
☐ Print Snow Output
☐ Print Vel./Depth Output
☐ Print MGT Output
☐ Print WTR Output
☐ Print Calendar Dates
Output File Variables: All

☐ Set CPU Affinity
CPU ID: 1

15. Click *SWAT Simulation* in the ArcSWAT menu and click on *Run SWAT*. The *Setup and Run SWAT Model Simulation* will appear allowing the user to make adjustments to the model run. Begin with the timeframe of the simulation by selecting a start and ending date under *Period of Simulation*. Click on *Skewed normal* for the rainfall distribution and 64-bit release. Click daily for the printout settings and adjust *NYSKIP* for the number of warmup years (Merwade & Rajib 2018). After clicking on the *Setup SWAT Run* button, the *Run SWAT* button will become available. Click the *Run SWAT* button to begin the simulation.



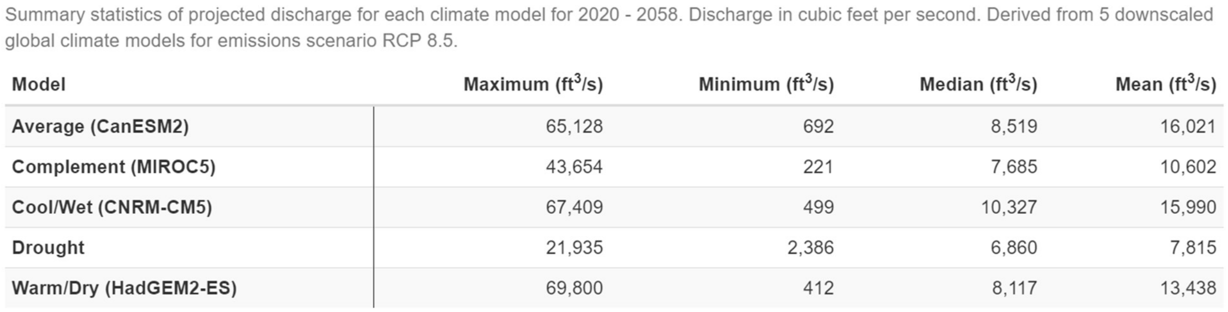
Check Output Files to Import

☑ output.rch ☑ output.sed ☐ output.snu
☑ output.sub ☐ output.rsv ☐ output.pot
☐ output.hru ☐ output.pst ☐ output.vel
☐ output.dep ☐ output.wtr ☐ output.wql
☐ output.snw ☐ output.swr ☐ output.mgt

Save current simulation as: (e.g., Sim1) Cachuma_Sim1

16. Select the output files to save in the project directory. Clicking on *Run Swat Check* performs a quality check to make sure the simulation run did not encounter any errors. Enter a name for the simulation and click the *Save Simulation* button.

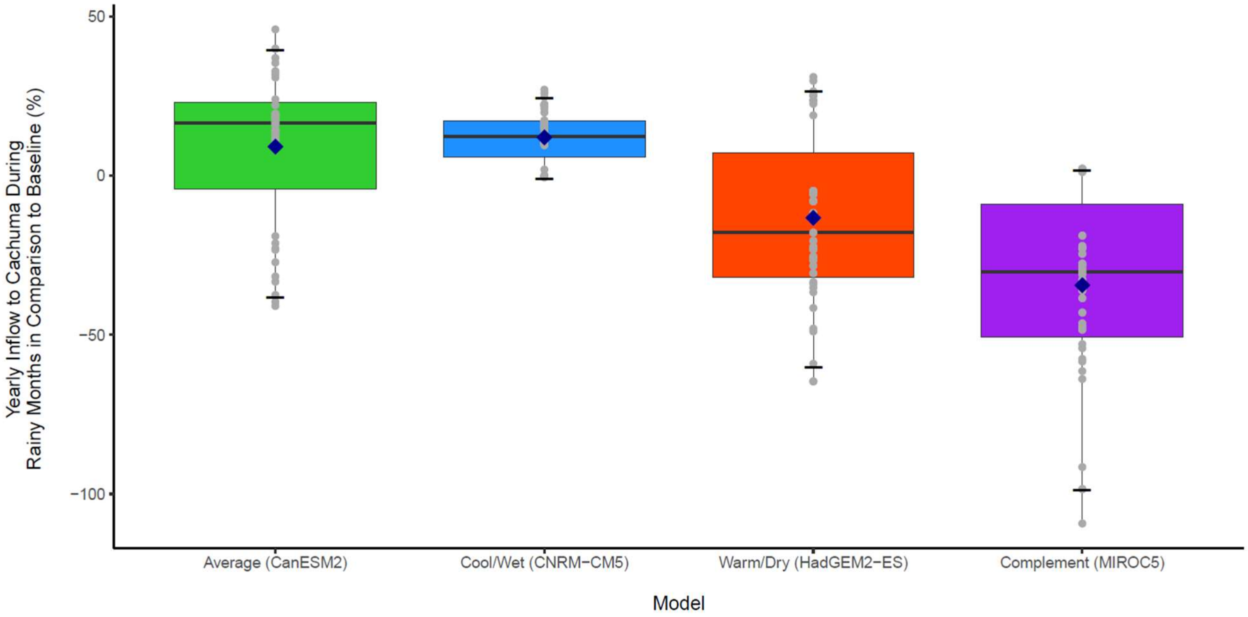
Appendix 7. Summary Statistics of Projected Discharge

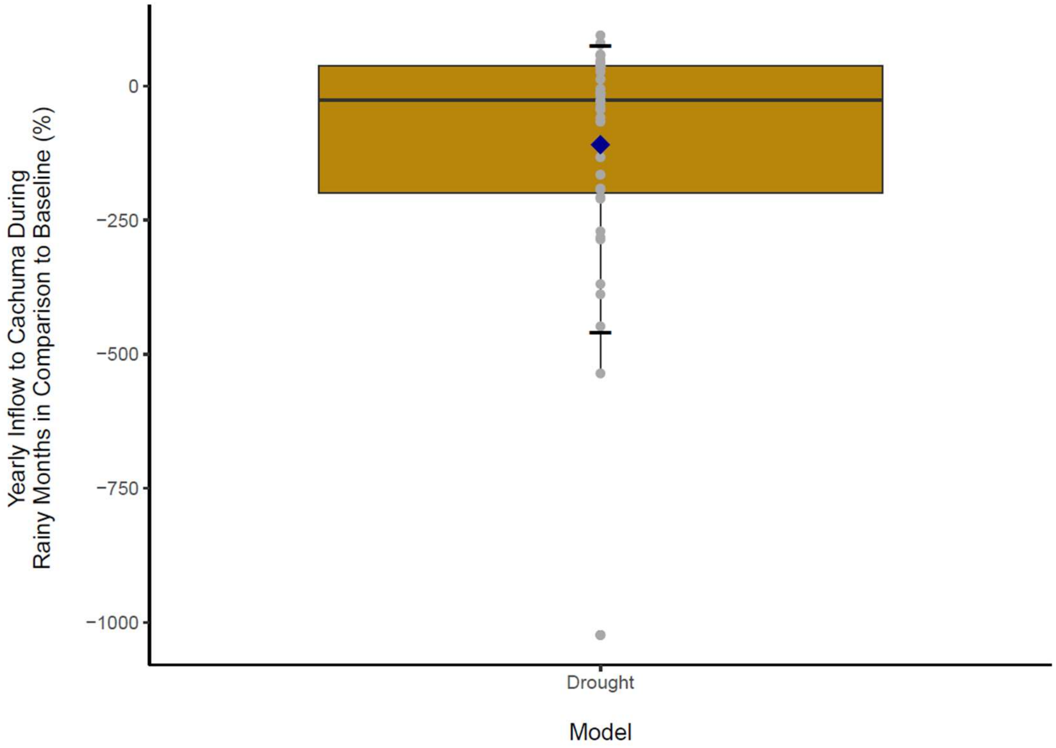


Summary statistics of projected discharge for each climate model for 2020 - 2058. Discharge in cubic feet per second. Derived from 5 downscaled global climate models for emissions scenario RCP 8.5.

Model	Maximum (ft^3/s)	Minimum (ft^3/s)	Median (ft^3/s)	Mean (ft^3/s)
Average (CanESM2)	65,128	692	8,519	16,021
Complement (MIROC5)	43,654	221	7,685	10,602
Cool/Wet (CNRM-CM5)	67,409	499	10,327	15,990
Drought	21,935	2,386	6,860	7,815
Warm/Dry (HadGEM2-ES)	69,800	412	8,117	13,438

Appendix 8. Percent Change in Yearly Inflow to Cachuma





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