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Technical Memorandum

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Subject: Flume Replacement Alignment Study (FRAS):
Technical Memorandum #7- Predictive Modeling Long-term Yield (FRAS Climate Study)

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List of Abbreviations

AF	acre-feet
AFY	acre-feet per year
BC	Brown and Caldwell
CDF	cumulative distribution function
District	Vista Irrigation District
EVWTP	Escondido-Vista Water Treatment Plant
Flume	Vista Flume
FRAS	Flume Replacement Alignment Study
FY	Fiscal Year
GCM	General Circulation Model aka Global Climate Model
GHG	greenhouse gas
GIS	geographical information system
HABs	harmful algal blooms
LOCA	Localized Constructed Analogues
LWS	local water system (Warner Basin, Lake Henshaw, etc.)
NOAA	National Oceanic and Atmospheric Administration
RCP	representative concentration pathways
Rincon	Rincon del Diablo Municipal Water District
RRR	rainfall-runoff-recharge
SWB	soil-water-balance
TM	technical memorandum
TODD GW	TODD Groundwater
WY	water year

Section 1: Introduction

Vista Irrigation District (District) provides water to portions of northern San Diego County in California, including the City of Vista, and portions of San Marcos, Escondido, Oceanside, and unincorporated areas of the county. The District relies on several sources of supply, including local water from the Lake Henshaw basin and wellfields, imported water from the Colorado River and Northern California, and treated water from the Claude “Bud” Lewis Carlsbad Desalination Plant. Imported water is made available through the San Diego County Water Authority. The cost and availability of these resources vary over time, and future supplies may become more expensive or less reliable. This is important to consider as the District anticipates an increase in future population served.[1]

Local Water System. Figure 1-1Figure shows the major components of the Local Water System (LWS). Lake Henshaw is a drinking water reservoir that captures rainfall and surface water runoff from the upper San Luis Rey watershed. During dry years, the District pumps groundwater into the reservoir from the Warner Valley Groundwater Basin. Water is released from Lake Henshaw into the San Luis Rey River which captures natural runoff downstream of Lake Henshaw as it flows 10 miles to the Escondido Canal Diversion Dam. The Escondido Canal diverts water from the San Luis Rey River through 14 miles of canal to Lake Wohlford.

As the water flows from Lake Henshaw to Lake Wohlford, it passes through the La Jolla, Rincon, and San Pasqual Indian Reservations, in addition to federal and private lands. A portion of the water is diverted from the Escondido Canal to the Rincon Band of Luiseño Indians (Rincon), consistent with the San Luis Rey Indian Water Rights Settlement Act (Settlement Agreement). The amount diverted to Rincon is calculated based on historical natural flow and is projected to be approximately 2,900 AF per year. Water from Lake Henshaw and the San Luis Rey River also supports in-stream uses for the La Jolla Band of Luiseño Indians.

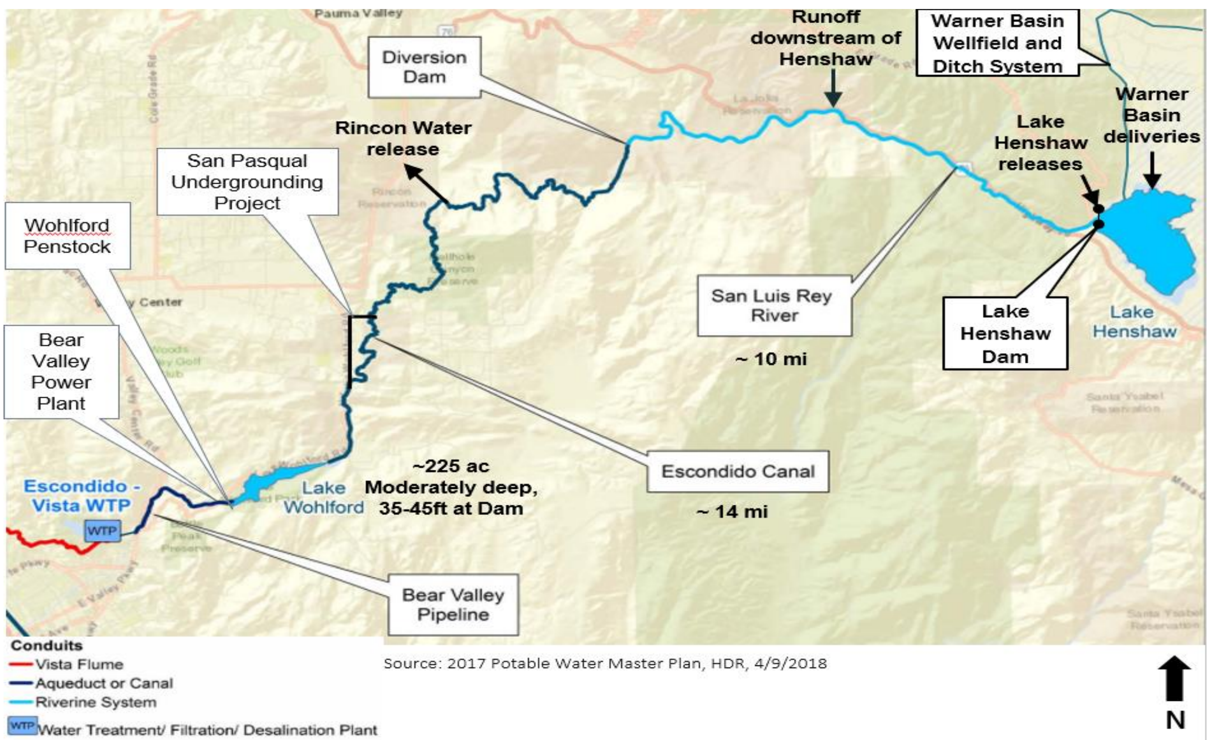

Figure 1-1. Overview of Lake Henshaw and LWS

Source: 2017 Potable Water Master Plan

[1] In 2020, the District served a population of approximately 134,600 and is projected to serve 156,600 by 2045 (District, 2020).

Water not diverted for Rincon travels through the Escondido Canal to Escondido Creek at the north end of Lake Wohlford. From Lake Wohlford, water passes through the Wohlford Penstock, passing through the Bear Valley Power Plant, and through the Bear Valley Pipeline as it makes its way to the Escondido-Vista Water Treatment Plant (EVWTP). The water is then filtered, treated, and transported via the Vista Flume for distribution to the District's service area. Current operational and treatment constraints at the EVWTP require that a blend ratio of 40:60 (local water to imported water) be maintained with a maximum of 40 percent local water. Operational constraints and information on water allocation is elaborated in a later section of this memo.

Local water yield is impacted by climate, including variations in dry and wet years. The service area features a Mediterranean climate with mild temperatures throughout the year. Future climate may result in greater variations from current and historical temperature and precipitation patterns.

Previous Studies. Several key studies were reviewed in preparation of this Technical Memorandum (TM). An Evaluation of Local Supply study was completed in 2002 by Bookman-Edmonston Engineering Inc. (Bookman-Edmonston Engineering, 2002). Brown and Caldwell (BC) used this study as a reference to understand watershed boundaries and hydrologic characteristics.

In 2018, the District completed the Warner Valley Basin Groundwater Flow Model Development and Calibration report with TODD Groundwater (TODD GW). This report estimates existing and potential future yield from the Warner Basin, the District's primary groundwater basin (TODD GW, 2018). The report includes results of a numerical groundwater flow model (the Rainfall-Runoff-Recharge [RRR] spreadsheet model) and considers future climate change scenarios using California Department of Water Resources guidelines. These climate scenarios include estimating future conditions up to the year 2075 for extreme wet, dry, and central tendency future conditions. BC worked with TODD GW and referenced this study to understand groundwater conditions and the groundwater basin's sustainable yield (the maximum quantity of water that can be withdrawn from the groundwater basin and not cause undesirable results, i.e., over drafting the aquifer). BC and TODD GW also coordinated throughout BC's modeling effort in performing reasonableness checks for BC's hydrologic model. Both firms also coordinated in data sharing to support both the contents of the analysis presented in this TM, as well as support for future wellfield optimization studies.

In 2020, the District completed a Water Supply Planning Study (WSPS) to assess long-term water availability and identify actions needed to maintain reliable sources of supply. As part of this study, The District evaluated the costs of operating, maintaining, and upgrading the LWS, including replacement of the Vista Flume (Flume) which is used to convey water from the EVWTP to Pechstein Reservoir. This evaluation to determine whether to replace the Flume was known as the *"To Flume or Not to Flume"* evaluation. The WSPS found that replacing the Flume (pursuing the *"To Flume"* option) and utilizing local water supplies is more reliable and cost-effective than supplementing those supplies with purchased water from other sources. On April 1, 2020, the District's Board of Directors voted to advance the *"To Flume"* option to its planning stage. The District then contracted with BC to conduct the Flume Replacement Alignment Study (Alignment Study) which seeks to answer the question, *"How to Flume?"*.

The Alignment Study evaluates the costs and benefits associated with alternative alignments and investment scenarios that include various infrastructure improvements. This study included several phases of work including:

- Phase 1: Project Initiation
- Phase 2: Alternatives and Evaluation Criteria Development
- Phase 3: Coarse Screening (results and recommended alignments shortlist)
- Phase 4: Fine Screening (proposed project selection)
- Phase 5: Recommended Alignment Report (RAR)

The results of the Alignment Study, and ultimately the answer to the *"How to Flume"* question for the District, depends on the cost of the new flume and on the long-term predicted yield of local water system. The local water system must reliably provide enough water over the long term to justify the cost of improvements. The Alignment Study effort also included a Balance Scale Affordability Check-in (Balance Scale Check-In), which includes an economic analysis to determine the financial viability of the Flume replacement project and established a LWS yield threshold of 2,700 AFY that must be met to enable financial viability. This effort also included an analysis of what potential effects a future Harmful Algal Blooms (HABs)-related project could have on the financial viability of a Flume replacement project. This is an important consideration as HABs incidents in Lake Henshaw have significantly impacted the District's use of Lake Henshaw and ability to reach the full potential of the system's local yield. In addition to HABs considerations, the Board of Directors requested that the Balance Scale Check-in closely consider how future climate might affect local yield.

To support this request, BC performed detailed modeling of the Lake Henshaw basin and the LWS to develop estimates of local yield, including consideration of future conditions that cover a wide range of potential changes in climate (i.e., higher temperature and more variable precipitation). This modeling effort is the Flume Replacement Alignment Study Predictive Modeling Long-term Yield (FRAS Climate Study), conducted as part of the larger Alignment Study project.

Purpose and Objectives of the FRAS Climate Study. The purpose of this study is to evaluate the potential impact climate change may have on future local water system yield. The results of this analysis help inform decision making for future infrastructure investments.

Local water yield is impacted by climate, including variations in dry and wet years. Future climate may result in greater variations from current and historical temperature and precipitation patterns. BC conducted the study presented in this TM to assess three future climate conditions and apply these conditions across five different infrastructure investment scenarios. Content of this TM documents the modeling efforts performed by BC and presents results for each of the LWS investment scenarios. The following objectives were achieved through this study and are reflected in components of Figure 1-2:

1. Use existing studies and work performed by the District's hydrogeology consultant (TODD GW) to understand watershed conditions, and support development of models that are representative of the LWS.
2. In addition to baseline conditions (historical climate), perform analysis to estimate a range of future climate conditions including a drier future and a wetter future, and use this information to inform changing conditions in the hydrologic model.
3. Develop a hydrologic model (the Soil-Water-Balance [SWB] model) to perform hydrologic simulations and estimate surface water runoff to Lake Henshaw and include accounting for variations in temperature and precipitation.
4. Develop a water system operations model (the GoldSim model) to simulate inputs, outputs, and conveyance of water from Lake Henshaw to Lake Wohlford, where it is subsequently delivered to the EVWTP. This includes simulations through the operations model that represent water system operations under proposed investment scenarios and calculate the local yield produced by the LWS at Lake Wohlford.
5. Compare the District's share of local yield estimates with the amount identified as the break-even point for justifying the cost of improvements.

Figure 1-2 provides a high-level summary of the different components of the FRAS Climate Study. Each of these components supports achieving the above objectives and overall purpose.

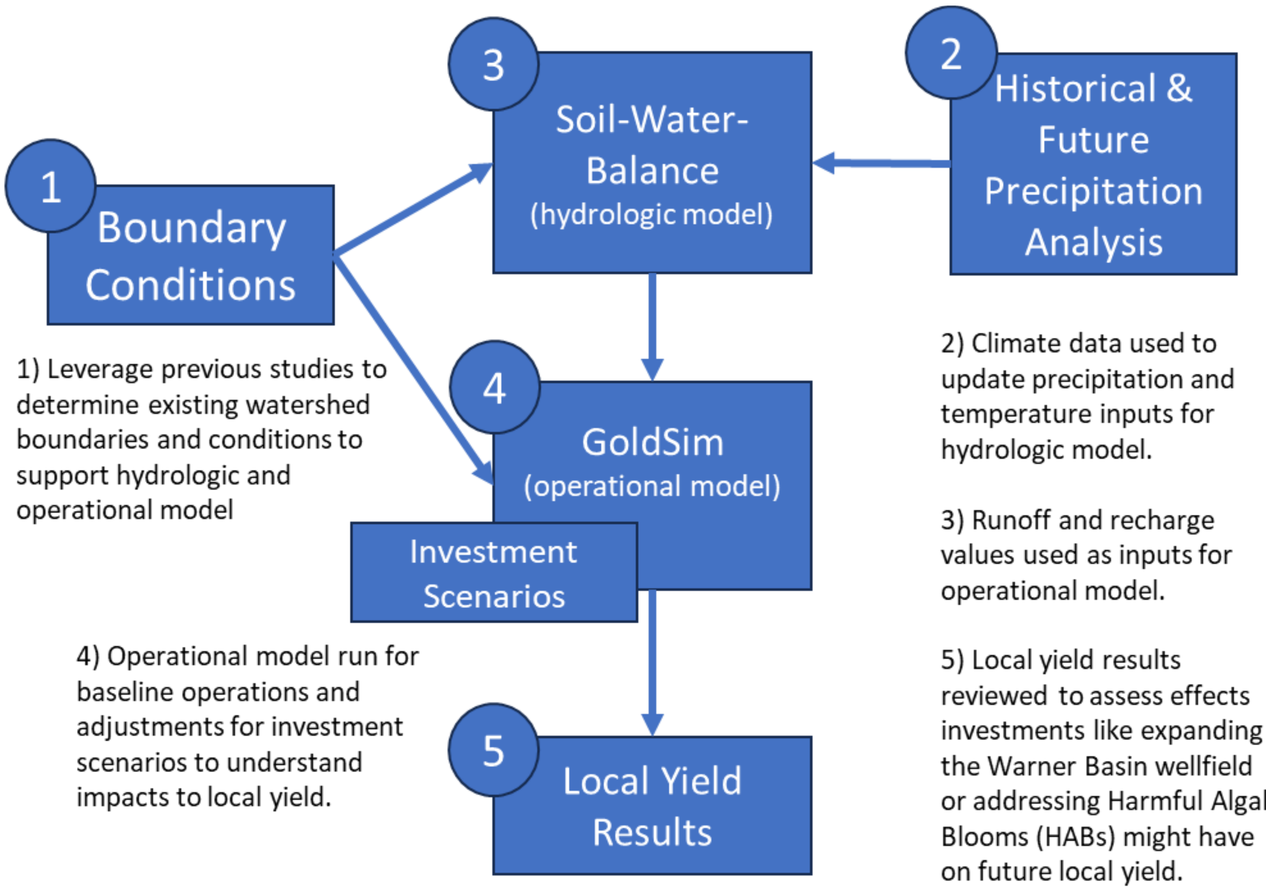

Figure 1-2. Summary of process flow for the FRAS Climate Study

This TM is structured as follows to support documentation and fulfilment of the above purpose and objectives:

- **Section 1 Introduction** provides basic background information on the District's LWS and the purpose of this study, building upon past work. Contents of this section introduce the previous studies that have led to and are supported by this study.
- **Section 2 Historical and Future Precipitation Analysis** includes a description of historical precipitation data and how to understand and estimate potential future changes to precipitation from climate change.
- **Section 3 Development of the Soil-Water-Balance Model** describes the hydrologic model developed and used to estimate changes in runoff within the watershed. Runoff values from this model are used as an input for the operational model (GoldSim) described in section 4.
- **Section 4 GoldSim Model Development describes** the operational model developed and used to understand the range of LWS yield for historical and proposed future conditions. These future conditions include parameters to represent different infrastructure investment scenarios.
- **Section 5 Results** presents projected local yield results from the GoldSim model and describes which of the annual average local yield values economically support the "to flume" replacement project.
- **Section 6 Conclusion** summarizes the analysis and key findings.

Section 2: Historical Precipitation Analysis and Future Climate Conditions Analysis

The analysis outlined in this TM considered the range of past historical precipitation and considered potential future impacts using modeled climate projections. The first step in the analysis was to develop a full historical precipitation time series, and then to identify a representative 30-year historical period to serve as the hydrologic baseline for studying climatological variabilities.

Establishing a hydrologic baseline using historical precipitation data helps in predicting future climatological effects. Distilling the data down to a representative, baseline 30-year period is a typical approach used to limit the period of analysis for future conditions.[2] From this representative baseline, BC developed future climate scenarios using climate model adjustments factors called "delta change factors."

2.1 Historical Precipitation Analysis

BC obtained historical observed daily precipitation data from the National Oceanic and Atmospheric Administration (NOAA) at Henshaw Dam (Station USC00043914) (accessed via National Centers for Environmental Information (NCEI)). BC filled gaps in precipitation data using nearby weather gauges. Table 2-1 summarizes the precipitation data sources and methods used to fill missing data at the NOAA Henshaw Dam gauge and provides the names of the nearby weather gauges. Daily precipitation data from the NOAA Henshaw Dam gauge were 98.4 percent complete for the historical record spanning from September 1942 through May 2023. Gaps in the NOAA Henshaw Dam record were filled using data from nearby gauges scaled by the ratio of average annual rainfall between NOAA Henshaw Dam and the nearby gauge. Remaining data gaps were filled using PRISM Climate Group precipitation data for Henshaw Dam. PRISM Climate Group collects climate data from monitoring stations and develops spatial climate datasets. PRISM Climate Group has modeled time series datasets with climatologically-aided interpolation (CAI) since 1981. CAI identifies long-term trends to model climatic conditions on a daily and monthly basis (PRISM, 2023).

Table 2-1. Precipitation Data Records Used to Create a Continuous Long-Term Time Series

Data Source	Available Record	Average Annual Rainfall for Available Record (inches)	Ratio of Annual Rainfall between NOAA Henshaw Dam and Data Source
NOAA Henshaw Dam (USC00043914)	1942 to present	24.2	---
NOAA Warner Springs (USC00049447)	1906 to 1977	13.0	0.63
NOAA Julian Wynola (USC00044418)	1949 to 1988	25.2	0.99
PRISM Henshaw Dam	1981 to 2023	23.4	1.00

Data gaps from NOAA Henshaw Dam filled using the following nearby gauges:
1949-1977: 38 days filled with scaled NOAA Warner Springs
1977-1980: 277 days filled with scaled NOAA Julian Wynola
1981-2023: 144 days filled with PRISM Henshaw Dam

[2] Climate in a narrow sense is usually defined as the average weather, or more rigorously as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization (IPCC, 2021).

The historical precipitation analysis considered the subset of data for water years (WY)[3] 1943 through 2023. Figure 2-1 shows the historical annual WY precipitation record (blue) and highlights the driest period on record (green), as well as the chosen 30-year climate model baseline (pink). The driest period was specifically highlighted as a result of conversations with District Staff and a need to ensure that the Climate Study include and compare the selected baseline 30-year period with the driest years in historical record.

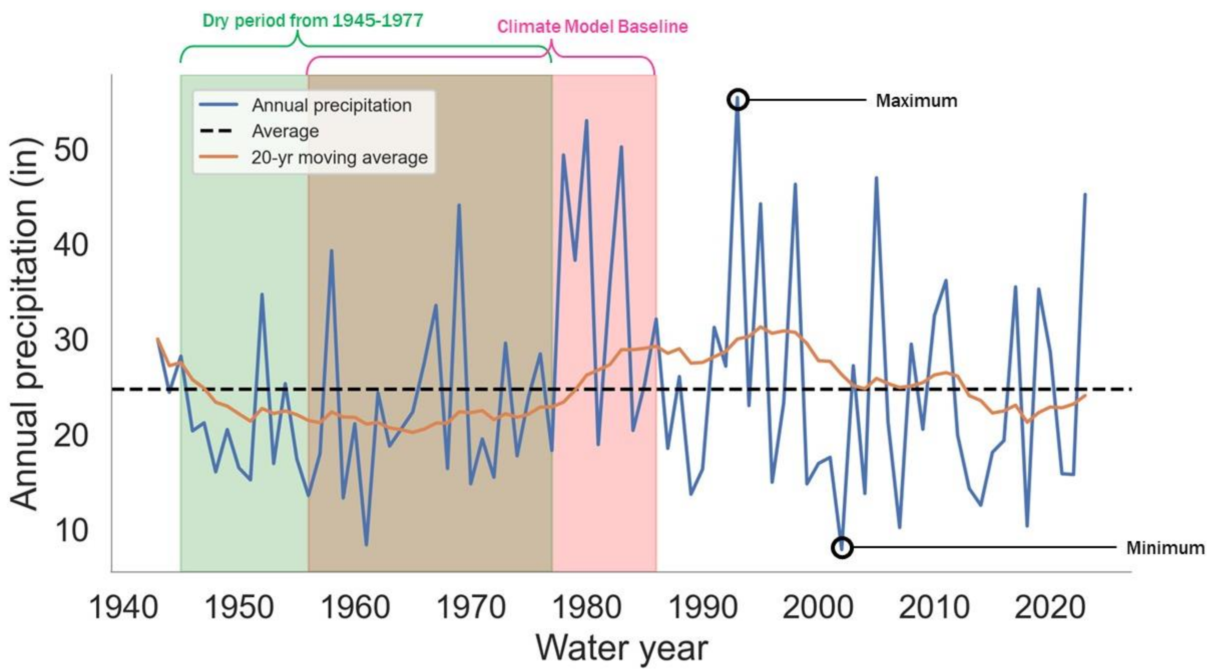

Figure 2-1. Historical annual WY Precipitation at Henshaw Dam

BC selected the 30-year climate model baseline period by considering every 30-year period within the subset of the historical record (WY 1943 – 2023) using a 30-year sliding window analysis. BC performed a regression analysis to fit a log-normal probability distribution to the annual rainfall totals for each 30-year window. BC then plotted these distributions and compared each 30-year period to the subset of the historical record using kurtosis and skewness. The 30-year window between WY 1957 and 1986 was most representative of the subset of the historical record and was therefore selected as the 30-year climate model baseline period. Figure 2-2 shows the probability distribution of WY precipitation from all 30-year periods (gray lines), the subset of the historical record (blue line), and the selected 30-year climate model baseline period (WY 1957-1986).

[3] A water year is defined as the 12-month period from October 1st to September 30th and is associated with hydrologic seasons. This timeframe begins with the start of the soil recharge season and ends with season of maximum evapotranspiration (American Meteorological Society, 2012).

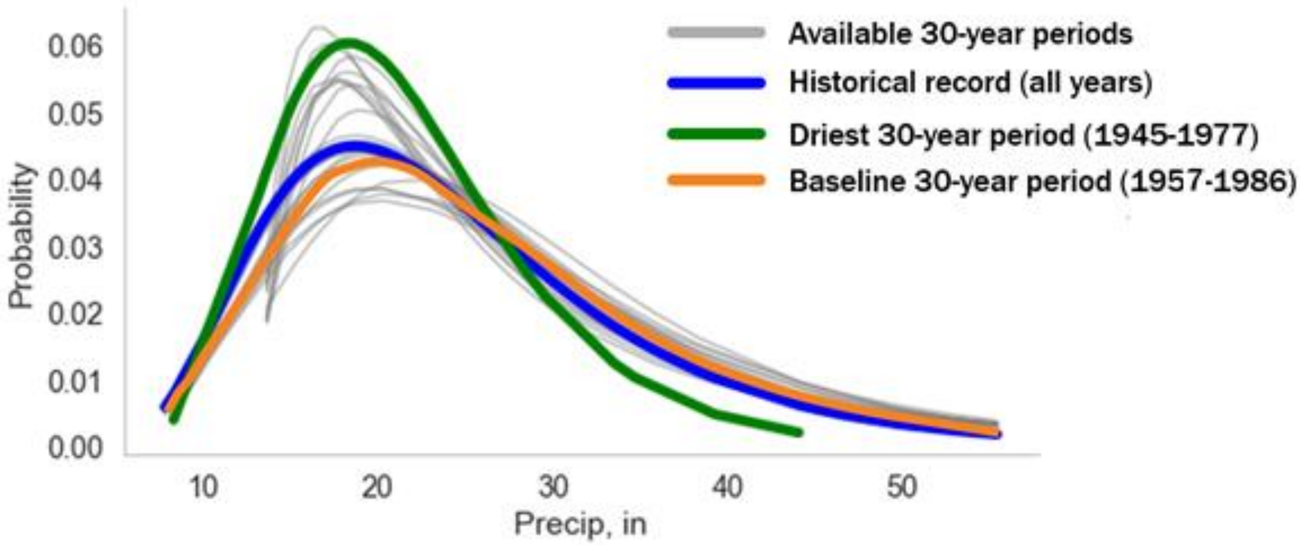

Figure 2-2. Comparison of probability distributions for annual precipitation over a sliding 30-year time window

This 30-year climate model baseline period captured comparable dry-year values to those in the 1945 to 1977 dry period (green line) without neglecting the wetter periods observed in the historical record. BC computed summary statistics shown in Table 2-2 to confirm this climate model baseline is a reasonable representation. Comparison of statistical parameters for the dry period, 30-year climate model baseline period, and historical record is summarized in Table 2-2.

Table 2-2. Comparison of Precipitation Statistical Analysis Results

Parameter	Dry Period WY 1945 to 1977	Climate Model Baseline Period WY 1957 to 1986	Historical Record WY 1943 to 2023
Mean	20.5	24.3	22.4
Median	20.3	23.1	21.1
Minimum	8.3	8.3	7.9
Maximum	43.8	53	55.2
Standard Deviation	1.4	1.6	1.6
10th Percentile	14.9	15.3	13.7
90th Percentile	32.8	44.7	43.8

The probabilities for Extreme Dry to Extreme Wet water years were calculated for the baseline period and compared to the dry period. Results of the comparison are summarized in Table 2-3. Statistically, the baseline period captures nearly the same probability of extreme dry years (12.9 percent) as found in the driest 30-year period on record but manages to also capture extreme wet water years (9.7 percent). The driest period does not capture any extreme wet years (0.0 percent). Using the driest period for the baseline could significantly skew predictive local yields results because this bias would be exacerbated once climate delta change factors are applied. The goal in selecting the baseline 30-year period is to establish an unbiased period that is representative of the overall year-to-year variability of precipitation. This approach provides the ability to estimate annual probabilities for risk and reliability.

Table 2-3. Comparison of Historical Baseline (1957-1986) to Historical Driest Period (1945-1977) by Water Year Type Probabilities

Water Year Type	Dry Period WY 1945 to 1977	Baseline Period WY 1957 to 1986
Extreme Dry	12.1%	12.9%
Dry	33.3%	22.6%
Normal	42.4%	35.5%
Wet	12.1%	19.4%
Extreme Wet	0.0%	9.7%

a. Extreme Dry was defined as water year precipitation less than the 10th percentile of the overall historical period.
b. Dry was defined as water year precipitation between the 10th percentile and half a standard deviation below the mean.
c. Normal was defined as between half a standard deviation below and above the mean.
d. Wet was defined as water year precipitation between half a standard deviation above the mean and the 90th percentile.
e. Extreme Wet was defined as water year precipitation above the 90th percentile.

2.2 Future Climate Conditions

In the coming decades, California is projected to see higher temperatures, more-variable precipitation, and increasing drought severity (Bedsworth et al., 2018). These changes will affect hydrologic processes within local watersheds, and consequently, will affect LWS yields. Therefore, the BC team evaluated water system yields under both historical and future climate conditions. The following sub-sections describe how BC developed future time series inputs for temperature and precipitation.

2.2.1 Global Climate Modeling

The World Climate Research Program facilitates climate change research through the Coupled Model Intercomparison Project (CMIP), which provides a framework for coordinated climate change modeling experiments. The fifth phase of CMIP, known as CMIP5 (Taylor et al., 2012), produced an extensive dataset of future climate projections based on General Circulation Model (GCM; often referred to as Global Climate Model) simulations by research groups from around the world. The Fifth Assessment Report by the Intergovernmental Panel on Climate Change relies heavily on CMIP5 results.

For CMIP5 experiments, GCMs were run using four scenarios known as representative concentration pathways (RCPs), each representing a different greenhouse gas (GHG) concentration trajectory. RCP scenarios are described below:

- **RCP 2.6:** A low trajectory representing an ambitious effort to reduce global GHG concentrations, with peak emissions occurring around 2020 before declining and becoming negative by 2100.

- **RCP 4.5:** A low to intermediate trajectory representing a substantial effort to reduce global GHG concentrations, with only a small increase in emissions before peaking around 2040.
- **RCP 6.0:** An intermediate trajectory representing a moderate effort to reduce global GHG concentrations, with peak emissions occurring near 2060 and then declining.
- **RCP 8.5:** A high trajectory representing no climate policies and a "business-as-usual" continuation of GHG emissions throughout the 21st century, associated with higher radiative forcing and therefore the greatest warming of all four RCPs.

2.2.2 Statistical Downscaling

GCM outputs must be adjusted for use at a local scale because climate models exhibit systematic error, or biases, due to limited spatial resolution, simplified physics and thermodynamic processes, numerical schemes, or incomplete knowledge of climate system processes (Navarro-Racines, 2015). This is evidenced by GCM simulations of historical time periods, which exhibit large errors with respect to historical observations (Ramirez-Villegas et al., 2013). Therefore, bias correction is often an integral part of downscaling GCM output for use in climate change impact studies (Pierce et al., 2015).

BC obtained GCM-based climate projections from the Cal-Adapt (https://cal-adapt.org/) data portal. The climate data from Cal-Adapt are derived from coarse-resolution GCM outputs that were bias corrected and downscaled using the Localized Constructed Analogues (LOCA) statistical method (Pierce et al. 2018). Cal-Adapt provides downscaled temperature and precipitation data for 10 GCMs covering a historical period (1950 to 2005) and a projected period (2006 to 2100) for two future emissions scenarios: RCP 4.5 and RCP 8.5. The 10 GCMs were selected by the California Department of Water Resources Climate Change Technical Advisory Group based on their relevance to water resources management in California (DWR, 2015).

2.2.3 Quantile Delta Mapping

Quantile mapping techniques are commonly used to correct systematic distributional biases in precipitation outputs from climate models. While standard quantile mapping techniques are effective at removing historical biases, this approach is known to alter raw model-predicted trends (Maurer et al., 2013; Maurer and Pierce, 2014; Switanek et al., 2017).

Standard quantile mapping techniques calculate error correction values using a historical calibration period and assume that the established error signal can be applied to any future time period. However, these error correction values can differ, in both magnitude and sign, as a function of quantile (Switanek et al., 2017). Standard quantile mapping techniques can significantly alter the model-predicted mean climate signal and can artificially reduce or increase variability on all time scales (Pierce et al., 2015). Researchers have developed adaptations on quantile mapping techniques that address these issues and preserve projected changes. The following numbered steps and Figure 2-3 describe the approach BC used to adjust precipitation data records for the Lake Henshaw basin. This proposed approach is largely based on quantile delta mapping methods described by Cannon et al. (2015) and Pierce et al. (2015).

1. **Select observed and projected rainfall data.** Observed rainfall data from the selected rain gauge (NOAA Henshaw Dam USC00043914) was obtained at a daily time step, along with historical and future results for the selected GCM and future emissions scenario.
2. **Prepare rainfall time series for a period of interest.** Extract model data for the desired future time frame, such as the late-century 30-year period from 2070 to 2099. Extract an equal duration (30-year) period of record from the observed data (e.g., the 1957 through 1986 baseline) and the concurrent data from the historical model run from the same GCM. The modeled data and observed data must use an equivalent time increment, which is daily data in this case.

3. **Calculate cumulative distribution function (CDF).** An empirical CDF is calculated for the 30 years of data from the observed and modeled historical datasets (1957 through 1986) and modeled future time frame (2070 to 2099), including zeros, and using a Weibull distribution:

$$P_i = \frac{i}{n+1}$$

   where P_i is the daily exceedance probability, i is the rank of the data point, and n is the total number of data points in the time series.

4. **Perform quantile delta mapping.** The CDF from the modeled historical time frame, $F_{m,h}[x_{m,h}(t)]$, is compared with the CDF from the modeled future time frame, $F_{m,p}[x_{m,p}(t)]$, where $x_{m,h}(t)$ is the modeled historical data and $x_{m,p}(t)$ is the modeled data for the projected period. A ratio is then calculated for each quantile, τ, in the CDFs of the same length. The resulting delta change, or change factor, denoted Δ_m, is calculated as follows:

$$\Delta_m(t) = \frac{F_{m,p}^{-1}\left[\tau_{m,p}(t)\right]}{F_{m,h}^{-1}\left[\tau_{m,p}(t)\right]}$$

   where $\tau_{m,p}(t)$ is the quantile for the model projected CDF at time t (Cannon et al. 2015). This calculation is performed for all quantiles spanning the data range.

5. **Apply delta corrections to observed data.** The delta change factors calculated in Step 4 are applied multiplicatively to the CDF for the observed dataset. The calculations are performed at equivalent quantiles for the selected time (t) as follows:

$$\hat{x}_{m,p}(t) = \Delta_m(t) F_{o,h}^{-1}\left[\tau_{m,p}(t)\right]$$

   where $\hat{x}_{m,p}(t)$ is the bias-corrected future projected value for time t. This calculation is performed for all quantiles spanning the data range.

6. **Reorder and correct for mean.** The bias-corrected data from Step 5 are re-ordered back into the original time series to preserve the observed rainfall patterns. The multiplicative adjustment preserves the median change from modeled historical to modeled future but does not necessarily preserve the *mean* change, since the quantile at which the mean falls can change in the future if the shape of the distribution changes (Pierce et al. 2015). Therefore, the following correction factor, K, is applied:

$$K = \frac{\langle x \rangle}{\langle \hat{x} \rangle}$$

   where $\langle x \rangle$ is the change in mean precipitation from the GCM, $\langle \hat{x} \rangle$ is the bias-corrected mean precipitation, and the angle brackets indicate that the mean is taken over the temporal window of interest (Pierce et al. 2015).

7. **Correct for dry days.** A second adjustment is performed to address zero-precipitation days. GCMs tend to produce too many days with small amounts of precipitation, sometimes referred to as the drizzle effect (Gutowski et al., 2003; Demirel and Moradkhani, 2015; Hawkins, 2016). A lower threshold is calculated by comparing the number of zero-precipitation days in the observed data with the number of zero-precipitation days in the concurrent modeled historical period (non-bias-corrected), where daily precipitation less than this threshold is set to zero such that the fractions of days with zero precipitation match between the two datasets. This fraction of zero-precipitation days is then applied to the bias-corrected data, where the smallest daily precipitation totals are set to zero to achieve an equivalent fraction.

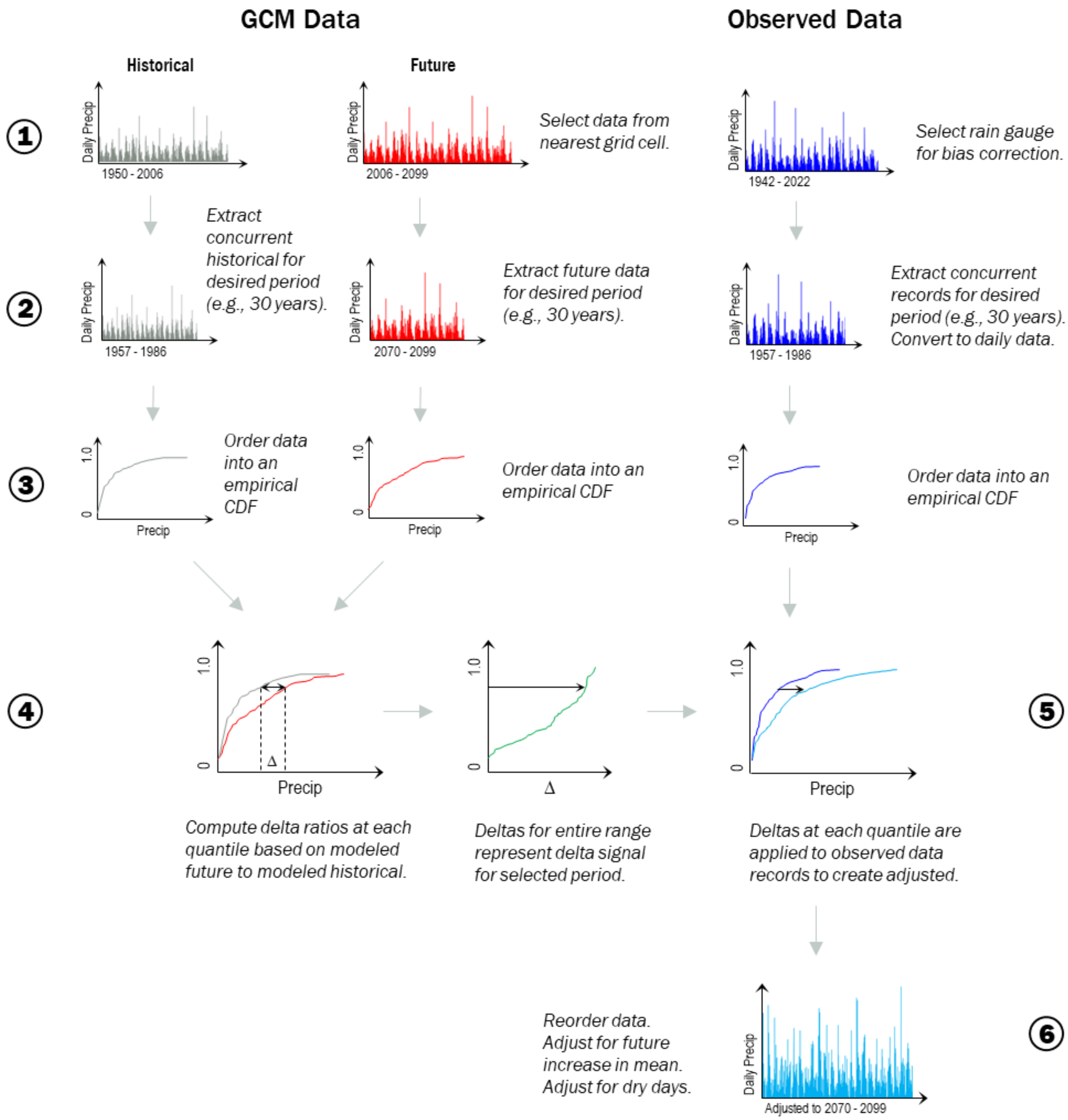

Figure 2-3. Quantile delta mapping procedure for developing climate-adjusted time series data

BC used a similar quantile delta mapping process to develop future minimum and maximum daily temperature time series; however, the correction for the mean and adjustment for number of dry days does not apply to temperature. After adjusted temperatures were reordered, some maximum-day temperatures were less than the minimum-day temperatures. In such cases, BC replaced the anomalies with data from the previous day.

2.2.4 GCM Selection

Future conditions can be defined by numerous combinations of emissions trajectory, time horizon, and selected GCM. Given limited time and resources, BC paired two future-condition scenarios with one historical-condition scenario to represent a wide range of conditions under which the water system must operate. BC chose to focus on late century (2070 to 2099) projections for RCP 8.5 because these tend to show the widest deviations from present conditions. BC then examined the projected average annual precipitation for each GCM to identify the wettest and driest conditions (Table 2-4).

Table 2-4. Average Annual Precipitation Projections by GCM for Late Century RCP 8.5

GCM	Average Annual Precipitation Projected for 2070 to 2099 (inches/year)	Difference from Historical Baseline for 1957 to 1986 of 24.3 inches per year
CMCC-CMS[a]	20.9	-14%
MIROC5	21.3	-12%
HadGEM2-CC	21.7	-11%
ACCESS1-0	21.8	-10%
GFDL-CM3	22.2	-9%
HadGEM2-ES	26.5	9%
CCSM4	26.9	11%
CESM1-BGC	27.9	15%
CNRM-CM5	34.7	43%
CanESM2[b]	35.1	44%

a. *CMCC-CMS was selected to represent the driest future condition.*

b. *CanESM2 was selected to represent the wettest future condition.*

BC selected CMCC-CMS to represent the driest future condition with approximately 14 percent less precipitation than the historical baseline. BC selected CanESM2 to represent the wettest future condition with approximately 44 percent more precipitation than the historical baseline. It is important to note that five of the 10 GCMs predict a drier future, while the other five GCMs predict a wetter future.

The time series inputs for temperature and precipitation generated in the future precipitation analysis were used as inputs for the SWB model runs to understand the range of potential projected conditions and impact to local surface water runoff and resources.

Section 3: Development of the Soil-Water-Balance Model

BC created a hydrologic model to support simulating water balance inputs and outputs for the watershed. This enabled BC to understand and model changes to the physical characteristics of the watershed, including potential changes in runoff and recharge values that influence the LWS' local yield. The SWB model was selected for the hydrologic model as it is based on peer reviewed code developed by the United States Geological Survey (USGS) to calculate spatial and temporal variations in groundwater recharge through the use of geospatial and climatological data. Four subwatersheds were identified within the Climate Study watershed. These are the Lake Henshaw, Intake, Siphon, and Lake Wohlford subwatersheds identified in Figure 3-1. One SWB model was developed for each subwatershed and is further described in the following subsections. Output from these models were used collectively as input into the GoldSim model for the previously described climate change analysis.

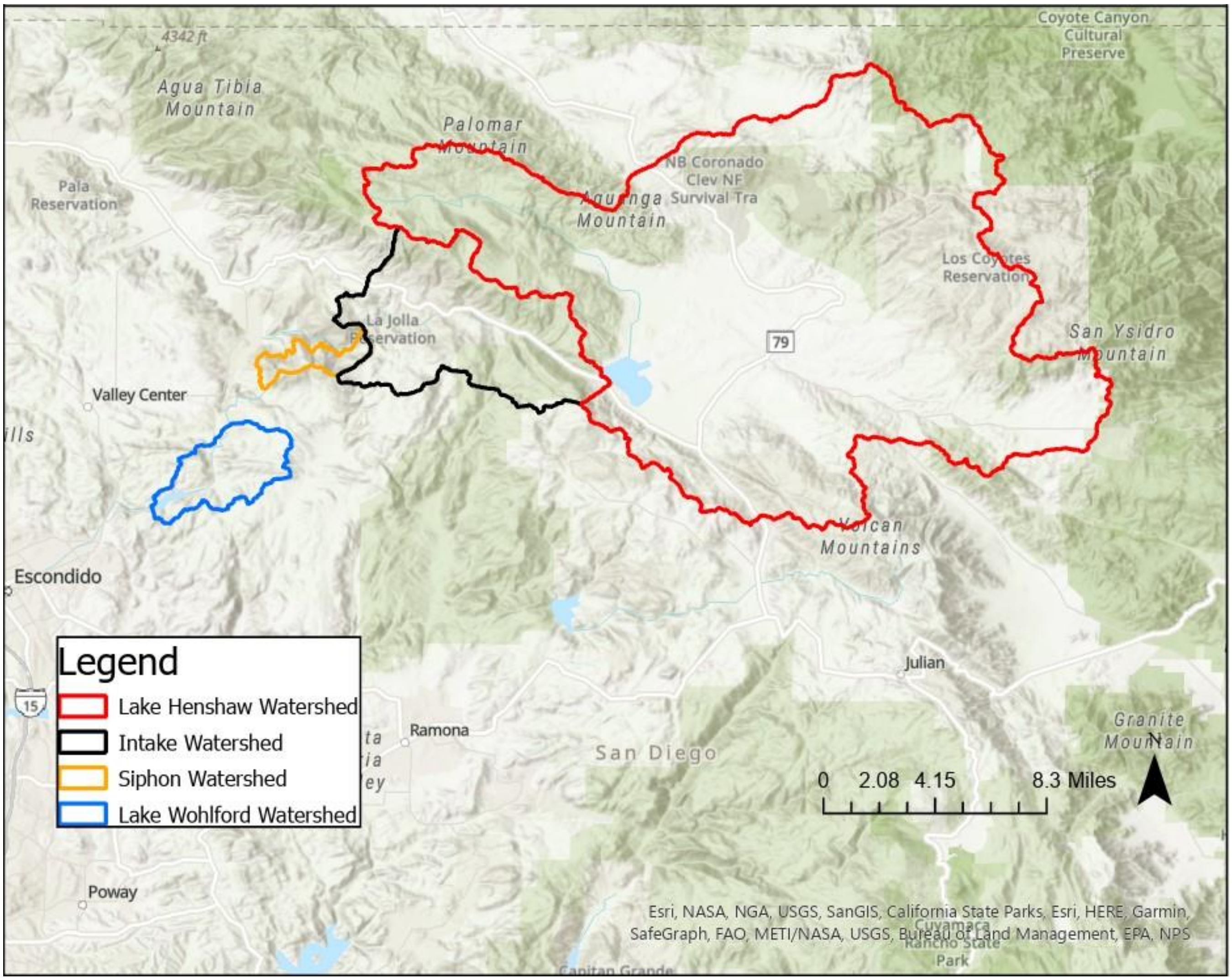

Figure 3-1. Map of subwatersheds used in the SWB model analysis.

3.1 Description of Soil-Water-Balance Model

The SWB computer code was used to estimate runoff and recharge estimates to understand changes in hydrologic conditions that contribute to variations in local yield. Recharge estimates produced by the SWB model are calculated as the difference between the change in soil moisture and sources and sinks. The calculation is based on a modified Thornthwaite-Mather soil-water-balance approach with outputs as daily, monthly, or annual values (Westenbroek et al., 2010). Sources of water are represented in the SWB code as precipitation, snowmelt, and inflow with sinks represented as interception, outflow (surface runoff), and evapotranspiration (ET). Sources and sinks of water in the SWB code are determined based on input climate data and landscape characteristics, further described in the following subsection.

The approach for this study required including a hydrologic model to understand potential changes in runoff and recharge for the basin. The SWB model was selected for this approach as it is a hydrologic model that is a peer reviewed resource from the USGS. This model was used to provide estimates of runoff and recharge and support understanding the water balance of the watershed. Climate data was used to help calculate potential future recharge and runoff values to the Warner Basin Wellfield and Lake Henshaw. The outputs of the SWB model were used as inputs for functions of the GoldSim model and enable connecting physical changes to the water basin with their potential operational impacts for the LWS.

3.2 SWB Model Inputs

The SWB code determines sources and sinks of water through inputs of climate data and landscape characteristics. The main SWB spatial inputs include land use, hydrologic soil types, available water capacity, flow direction, and daily values of precipitation and temperature. Other components of the SWB inputs include root zone depth, ET, and curve numbers determined by the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) curve number rainfall-runoff relation (Cronshey etal., 1986). The four SWB models were analyzed for years 1943 through 2022 for the purpose of this climate change analysis. This period was determined based on available historical climate data as previously discussed in Section 2. The SWB code estimates outputs based on calendar years (January through December). This output was adapted to water years (October through September) for input into the GoldSim model, further described in subsequent sections.

Data for each SWB model were obtained through various publicly available sources, including NRCS U.S. Department of Agriculture (USDA) Web Soil Survey for available water capacity and soil types and USGS National Land Cover Database for land use. As detailed in Section 2, minimum and maximum temperature and precipitation were obtained through the NOAA National Centers for Environmental Information and nearby weather stations. Curve numbers were set based on the NRCS USDA class of moisture condition defined as antecedent runoff condition II (Westenbroek et al., 2010). Root zone depth was initially set based on generic values for similar land characteristics and was refined through a performance evaluation history matching process.

The four main SWB spatial inputs for the Lake Henshaw Watershed are illustrated in Figure 3-2 through Figure 3-5. Available water capacity is shown in Figure 3-2 and was estimated to range from 0.67 inches per foot to 4.25 inches per foot in the Lake Henshaw Watershed based on the previously described NRCS USDA data. The four soil groups, represented in Figure 3-3, decrease in infiltration sequentially from soil group one to soil group four. A numerical representation of NRCS soil groups A through D (see Table 2-1) was necessary for illustrating the soil groups spatially by means of a color ramp. Soil group one represents the highest infiltration rate or lowest overland flow and is equivalent to the NRCS soil group A. Soil group four represents the lowest infiltration rate or highest overland flow and is equivalent to the NRCS soil group D. Table 3-1 describes the 15 land use types present in the Lake Henshaw Watershed based on the land use code.

Figure 3-4 illustrates the land use codes presented in Table 3-1. Of the 15 land use types, three types (mixed forest, shrub/scrub, and grassland/herbaceous) are the most abundant.

Flow direction, shown in Figure 3-5, determines how the SWB code will route overland flow between grid cells. The flow direction is based on the D8 flow-routing algorithm where a unique flow direction is assigned to each grid cell (Westenbroek et al., 2010). The direction is determined by the steepest slope between the central cell and its neighboring cells.

In the SWB code, root zone depth is set based on soil type and land use. Table 3-1 presents the root zone depths for the Lake Henshaw SWB model per soil group and land use. In the SWB code, root zone depth is multiplied by the available soil water capacity to gain the maximum soil water capacity. This is the maximum amount of soil-water storage that can take place in an SWB grid cell, any additional water will become recharge.

As previously mentioned, the SWB code requires spatial data for minimum, maximum, and average temperature as well as precipitation for the entire watershed. Average monthly temperature and total monthly precipitation are shown in Figure 3-6 for the full model time period of 1943 through 2022. A 30-year annual average based isopluvial map from the County of San Diego, Planning & Development Services was applied to the precipitation data to obtain a spatially varied precipitation signal. To gain spatial variation in temperature, an elevation correction was applied to the temperature signal based on the Lake Henshaw Dam station elevation. The spatially varied daily minimum and maximum temperatures were applied to the Hargreaves and Samani method in the SWB code to produce a spatially variable estimate of potential ET (Hargreaves-Samani, 1985).

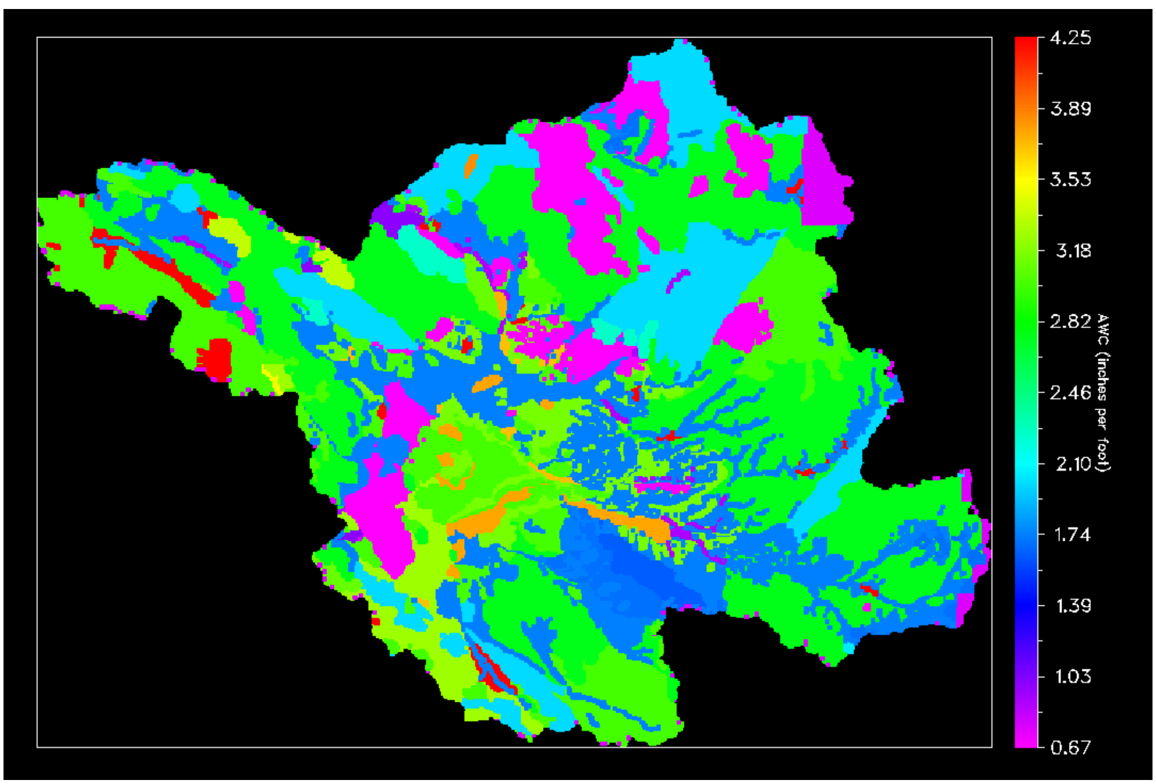

Figure 3-2. Lake Henshaw SWB inputs - Available Water Capacity (inches per foot)

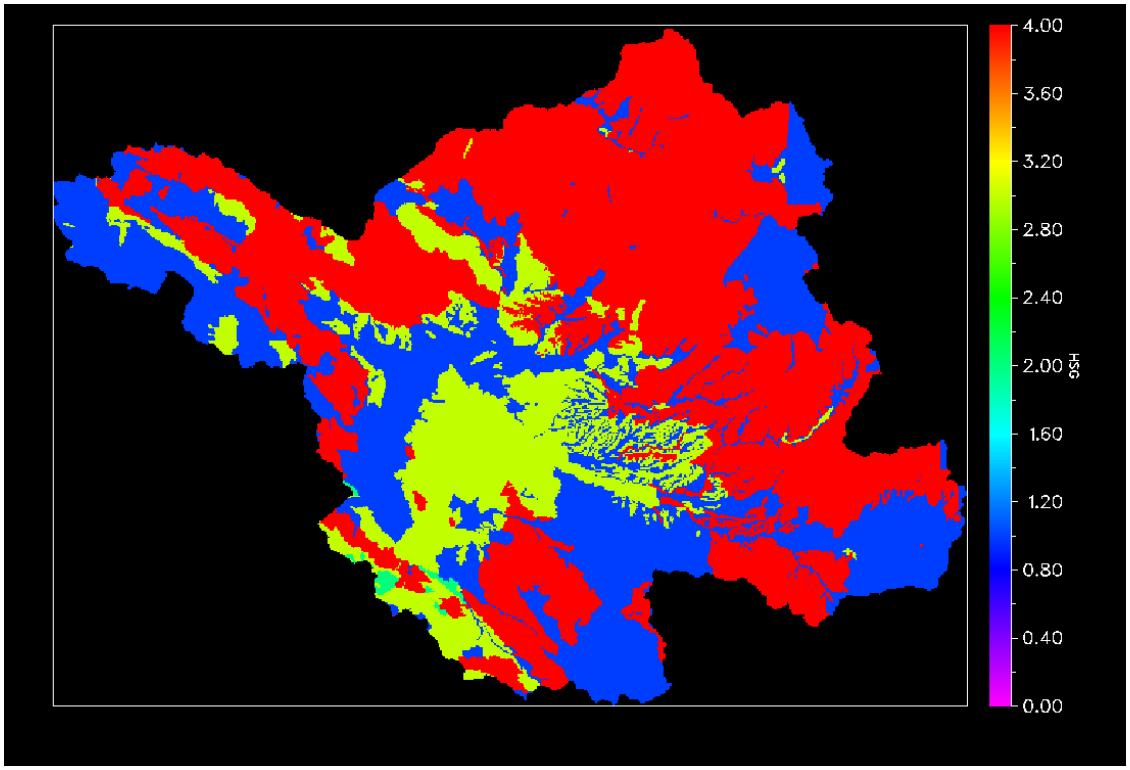

Figure 3-3. Lake Henshaw SWB inputs – Soil Groups

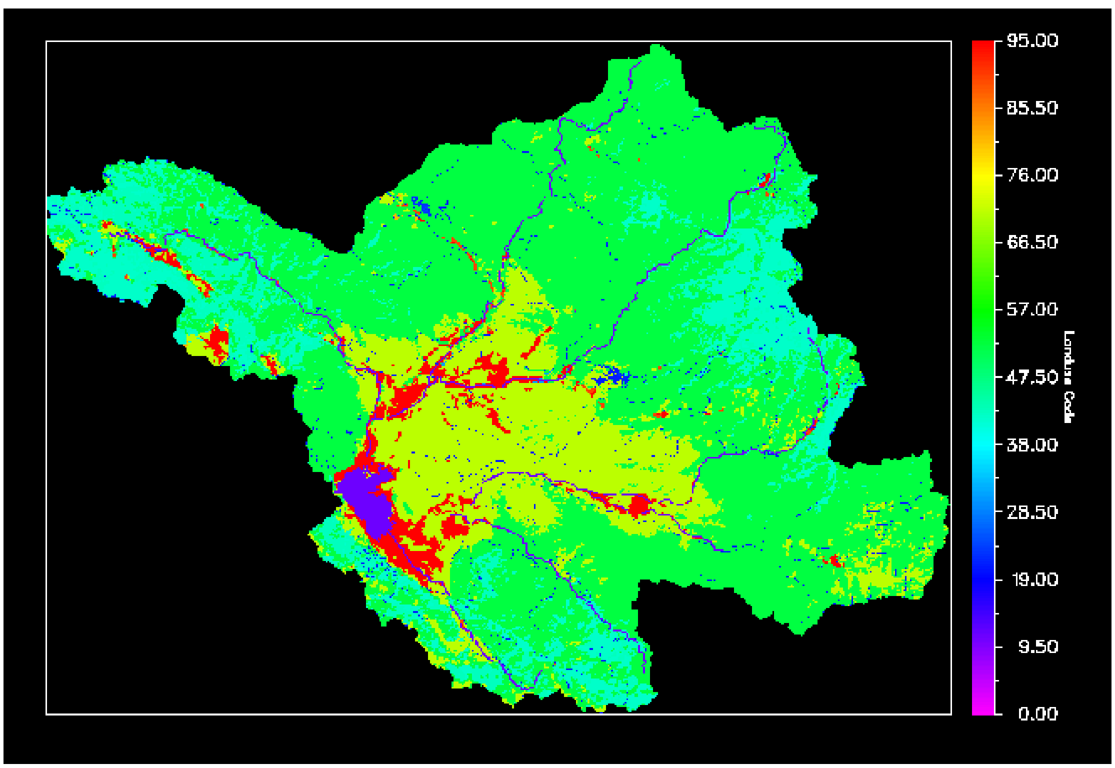

Figure 3-4. Lake Henshaw SWB inputs – Land Use

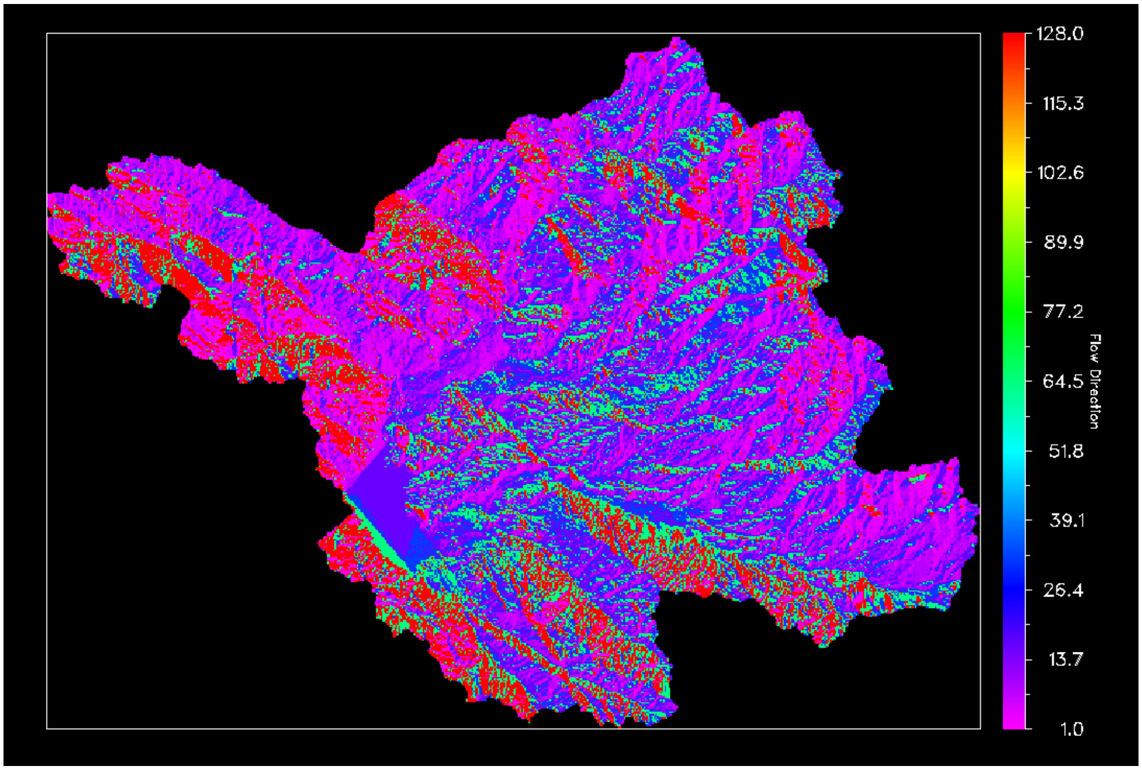

Figure 3-5. Lake Henshaw SWB inputs – Flow Direction

Table 3-1. Lake Henshaw SWB Land Use Code Descriptions and Correlating Root Zone Depths					
Land Use Code	Land Use Description	Root Zone Depth (feet)			
		Soil Group A	Soil Group B	Soil Group C	Soil Group D
11	Open Water	0	0	0	0
21	Developed, Open Space	6.1	7.6	4.85	3.05
22	Developed, Low Intensity	7.05	8.75	5.6	3.5
23	Developed, Medium Intensity	7.05	8.75	5.6	3.5
24	Developed, High Intensity	7.05	8.75	5.6	3.5
31	Barren Land (Rock/Sand/Clay)	2.3	2.3	2.3	2.3
41	Deciduous Forest	6.15	5.3	4.25	3.7
42	Evergreen Forest	7.2	6.05	4.85	4.25
43	Mixed Forest	6.7	5.65	4.55	4
52	Shrub/Scrub	5.6	7	5.6	3.7
71	Grassland/Herbaceous	5.1	6.4	5.1	3.4
81	Pasture/Hay	5.85	7.3	5.85	3.9
82	Cultivated Crops	4.85	4.4	4.3	3.1
90	Woody Wetlands	2.95	3.3	2.95	2.6
95	Emergent Herbaceous Wetlands	3.6	4	3.6	3.2

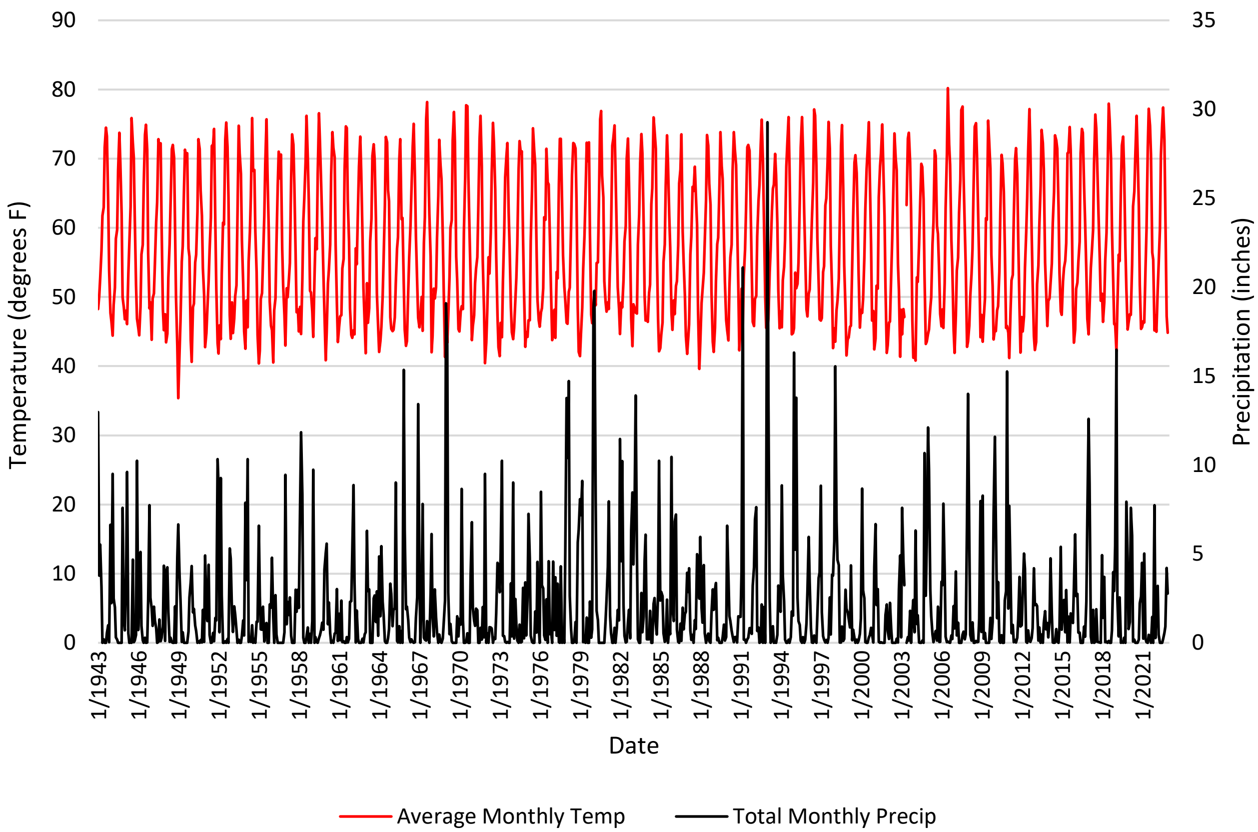

Figure 3-6. Lake Henshaw SWB inputs (average monthly temperature and total monthly precipitation)

Historical data (as provided in the above figure) Spatial inputs to the SWB code can vary in resolution. For each watershed, spatial resolution was determined based on subwatershed area with consideration of model run time. While a finer resolution can produce more spatially detailed results, it can also result in a longer model run time. The Lake Henshaw SWB model was set up as 60-meter resolution, the Intake SWB model as 100-meter, the Siphon SWB model as 80-meter, and the Lake Wohlford SWB model as 120-meter resolution. The Lake Henshaw Watershed was set at a finer resolution than the three subsequent watersheds to gain a more heterogeneous understanding of the focus area. While having a higher resolution in the Lake Henshaw basin increased model run time, it was pertinent to understanding the complexity within the watershed.

3.3 Lake Henshaw SWB Model Performance Evaluation

Several iterations of inputs were tested for the Lake Henshaw SWB model during the performance evaluation phase. This performance evaluation process was based on history matching SWB model results with a combination of USGS stream gauge data representing the behavior of the natural system and with available evaluations of water balance characteristics within the Lake Henshaw watershed. After an initial comparison to preliminary published data, the Lake Henshaw SWB model was compared to an existing Rainfall-Runoff-Recharge (RRR) spreadsheet model produced by TODD GW (TODD GW, 2018). The TODD GW RRR model encompasses the same watershed extent as the Lake Henshaw SWB model and was used by TODD GW in developing and calibrating a three-dimensional groundwater flow model for an area that includes the Lake Henshaw watershed. The TODD GW RRR model represents a relevant data set for comparison of the Lake Henshaw SWB results because the RRR model has been used in a more robust evaluation of groundwater to surface water interaction in an area that encompasses the Lake Henshaw watershed. Root zone depth, land use, and available water capacity were three of the inputs focused on for comparison with the TODD GW RRR model. Following Lake Henshaw SWB model input adjustments, the estimated recharge from the Lake Henshaw SWB model was compared to the TODD GW RRR model for the complete model domain. Two USGS streamflow gauges San Luis Rey and Agua Caliente shown in Figure 3-7, were used as comparison points for the estimated runoff from the TODD GW RRR model. The runoff estimates from the Lake Henshaw SWB model were also compared to the data from these gauge locations.

Figure 3-7. San Luis Rey and Agua Caliente USGS gauge locations and SWB sub-watersheds

The most sensitive input for modifying the Lake Henshaw SWB model output against the TODD GW RRR model was root zone depth. During the initial performance evaluation, the root zone depth was adjusted based on root zone depth values used in the calibrated TODD GW RRR model. As previously discussed, root zone depth is set based on land use and soil groups for the SWB code. In contrast to the SWB code, the root zone depth for the TODD GW RRR model is set based on land use and sub-watersheds. The designated land use between the two models is comparable; however, the 18 sub-watersheds in the TODD GW RRR model do not directly compare to the spatial distribution of the four soil groups in the Lake Henshaw SWB model. This discrepancy resulted in different root zone depth estimations for various areas within the Lake Henshaw SWB domain between the SWB and TODD GW RRR models. For the three dominant land uses in the Lake Henshaw Watershed (grassland/herbaceous, shrub/scrub, and mixed forest), the TODD GW RRR model included root zone depth values of 7 feet to 20 feet, respectively. Based on site-specific knowledge and discussion with TODD GW staff, BC determined this range for root zone depth to be too deep and instead estimated these values to be between approximately 3 feet and 7 feet for the three main land use designations in the Lake Henshaw SWB model, as BC considered these values to be more representative of site-specific conditions.

Following the root zone adjustments, estimated recharge from the Lake Henshaw SWB model was visually compared to recharge estimates from the TODD GW RRR model. Estimated runoff from the Lake Henshaw

SWB model for the two sub-watersheds denoted in Figure 3-8 were visually compared to runoff from the TODD GW RRR model for equivalent sub-watersheds and the two respective USGS streamflow gauges.

Figure 3-8 represents the final iteration of the Lake Henshaw SWB model recharge results in comparison to TODD GW's RRR model for the full model domain. Recharge estimated by the Lake Henshaw SWB model reproduces the recharge variation pattern present in the estimates from the TODD GW RRR model. In general, the recharge pattern reflects the precipitation pattern (Figure 3-6) and the highest peaks in recharge were greater in the Lake Henshaw SWB model than in the TODD GW RRR model. This may reflect the difference in root zone depth discussed above or differences in the way in which the SWB code and the TODD GW RRR model handle underflow, evapotranspiration, or storm event related overland flow components. These differences represent one uncertainty in the performance of both the RRR and SWB. There are no specific data available for recharge to use as direct comparison to actual behavior in the watershed, therefore additional SWB performance evaluation was conducted using runoff predictions from both the Lake Henshaw SWB model and the TODD GW RRR.

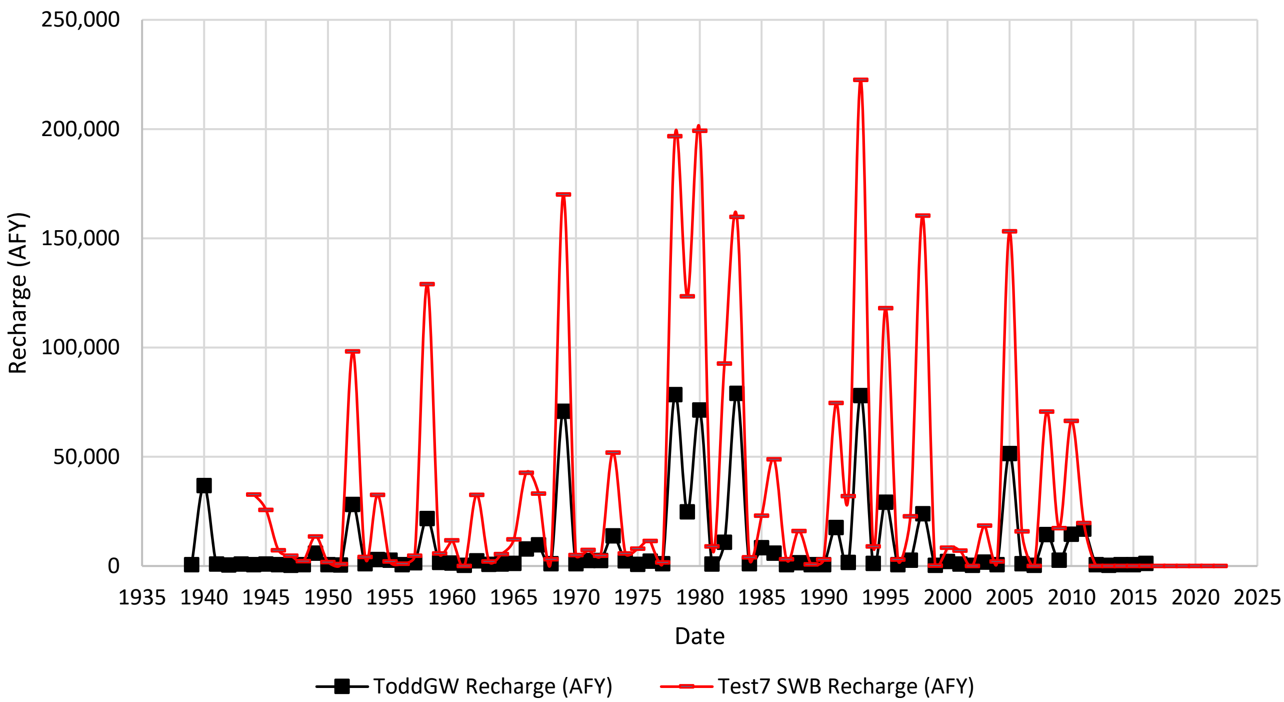

Figure 3-8. Lake Henshaw SWB recharge and TODD GW RRR recharge over water years

Runoff predictions for the San Luis Rey and Agua Caliente watershed areas (Figure 3-7) were calculated from the Lake Henshaw SWB model results and then compared to runoff generated from the TODD GW RRR model and USGS streamflow gauge data. Similar to the recharge results, the runoff estimated by the Lake Henshaw SWB model followed a comparable pattern as the TODD GW RRR model and the USGS gauge data for both sub-watersheds (Figure 3-8 and Figure 3-9). In addition to this comparison, these figures include the average runoff values for the Lake Henshaw SWB and TODD GW RRR models which provides a reasonable comparison of the overall total runoff in each modeled watershed. An average of USGS gauge data was not provided because the period of record is smaller than both the TODD GW RRR model and the Lake Henshaw SWB model simulation period and would therefore be less comparable.

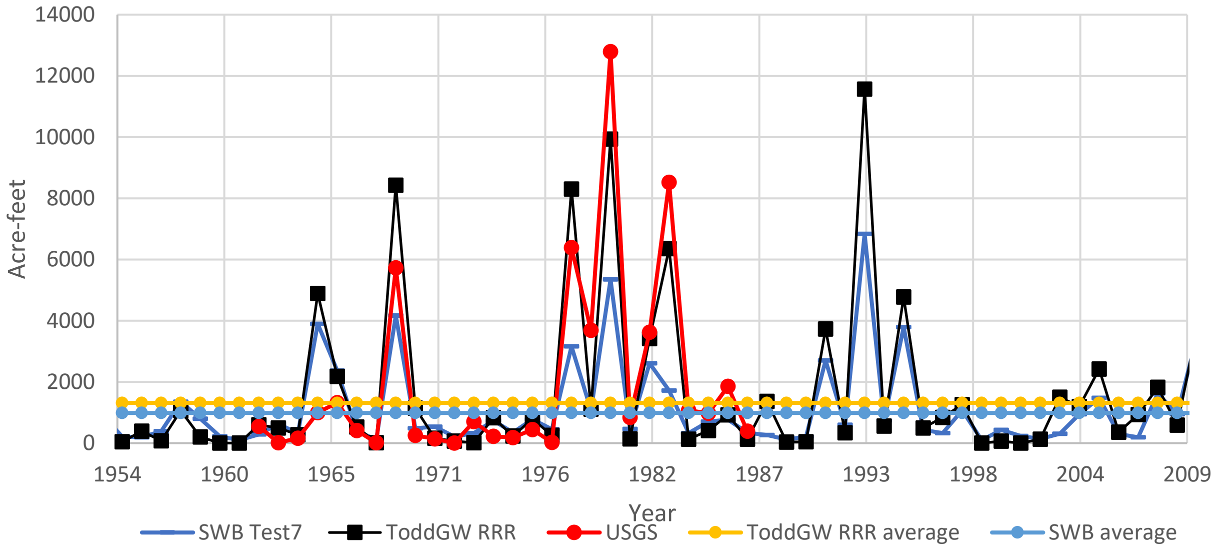

Figure 3-9. Agua Caliente sub-watershed average annual runoff for Lake Henshaw SWB, TODD GW RRR, and Agua Caliente USGS Gauge

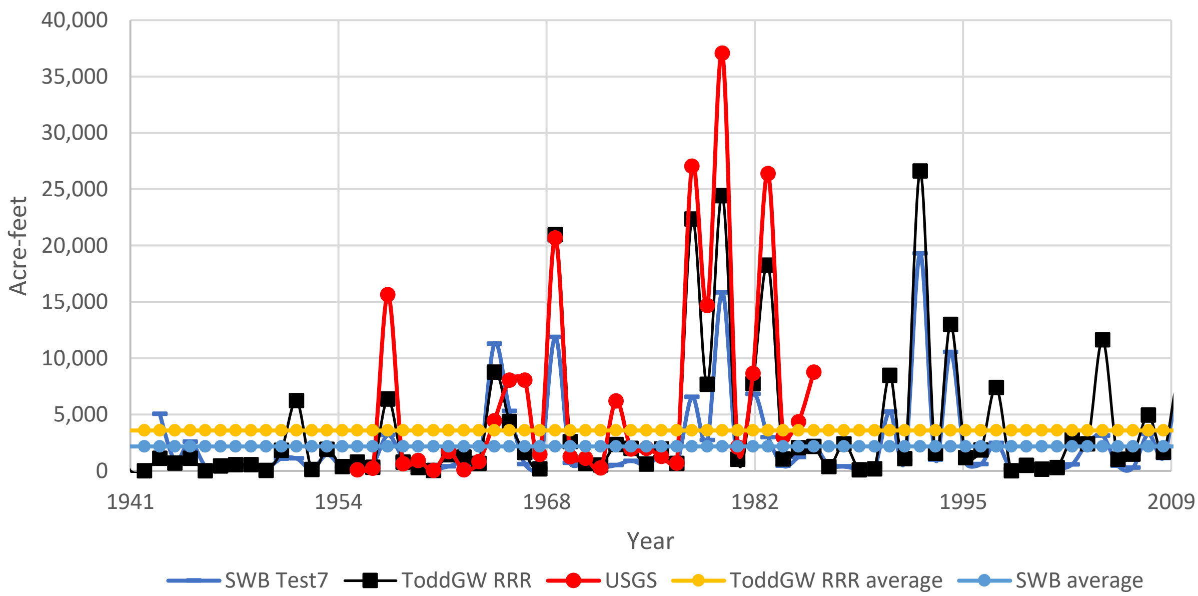

Figure 3-10. San Luis Rey sub-watershed average annual runoff for Lake Henshaw SWB, TODD GW RRR, and San Luis Rey USGS Gauge

Overall, the runoff predictions match trends and events, with the highest peaks in runoff generally lower in the Lake Henshaw SWB model. Further review of these figures also illustrates that the pattern of the runoff for both the TODD GW RRR and Lake Henshaw SWB models match well with the observed behavior at the respective USGS gauges, The SWB tends to predict lower runoff values during high flow storm events than either the TODD GW RRR prediction or the USGS gauge data. The TODD GW RRR predictions are also occasionally lower than the gauge data during peak flow events. This is likely the result of the Lake Henshaw

SWB and the TODD GW RRR models not providing complete or robust simulation of the stream flow or overland flow dynamics. Comparison of the average predicted runoff values between the TODD GW RRR and Lake Henshaw SWB models suggests that the total amount of runoff predicted by both TODD GW RRR and Lake Henshaw SWB models are relatively close given the overall range of natural runoff behavior. This close agreement suggests that the inherent uncertainty in both models is similar and that use of prediction results from the SWB models in the GoldSim model is acceptable.

To further evaluate the performance of the SWB, a reasonableness check was performed on the Lake Henshaw SWB model with published results from neighboring basins (Flint et al., 2012). The San Dieguito River Basin is located South of the Lake Henshaw Basin and is considered a comparable environment for the means of this analysis. The San Diego River Basin, located directly South of the San Dieguito River Basin, was used as an additional point of comparison due to limited published precipitation, runoff, and, and ET data for the San Dieguito River Basin. Table 3-2 presents four main parameters for comparison between the Lake Henshaw SWB results and published data for the San Dieguito Basin and the San Diego River Basin (Flint et al., 2012). All data presented in Table 3-2 were normalized to area and are represented in inches per year for two date ranges: approximately 1940 through 2009 to encompass the historical climate record for Lake Henshaw previously discussed, and 2000 through 2009 to represent a recent, dry decade as discussed in Flint et al. (2012).

Precipitation, runoff, recharge, and potential ET were compared between the Lake Henshaw SWB results and published data for the San Dieguito Basin and the San Diego River Basin (Table 3-2). Due to limited published data for the San Dieguito River Basin, recharge is the only comparable parameter for the basin. The Lake Henshaw SWB model results in a higher average than both the San Dieguito Basin and the San Diego River Basin but is considered reasonable for both date ranges. The remaining three parameters are also comparable and reasonable between the Lake Henshaw SWB model results and the San Diego River Basin. Overall, the results of this comparison suggest similar model performance as the performance identified in the comparison to the TODD GW RRR model described above. The recharge estimates developed in the Lake Henshaw SWB model are higher than those developed by Flint et al (2012) and the average runoff values are in reasonable agreement. No comparison to precipitation or potential evapotranspiration were performed and an in-depth review of the methodologies used in Flint et al (2012) was not attempted. The possible reasons for observed discrepancies in recharge have not been evaluated and are likely a combination of differing assumptions regarding input parameters and model capabilities.

Table 3-2. Lake Henshaw SWB, San Dieguito River Basin[a], and San Diego River Basin[a] Parameters

Date Range	Area		Precipitation (inches/year)	Runoff (inches/year)	Recharge (inches/year)	Potential ET (inches/year)
1944-2009	Lake Henshaw SWB model	Maximum	56.80	7.13	20.23	68.20
		Minimum	9.08	0.13	0.01	56.08
		Average	25.31	0.99	3.59	62.96
1940-2009	San Dieguito River Basin	Average	Unknown	Unknown	1.48	Unknown
1940-2009	San Diego River Basin	Average	15.35	0.51	1.89	51.18[b]
2000-2009	Lake Henshaw SWB model	Maximum	31.73	1.54	12.42	67.98
		Minimum	12.30	0.18	0.08	61.61
		Average	22.41	0.63	2.70	65.93

Table 3-2. Lake Henshaw SWB, San Dieguito River Basin[a], and San Diego River Basin[a] Parameters						
Date Range	Area		Precipitation (inches/year)	Runoff (inches/year)	Recharge (inches/year)	Potential ET (inches/year)
2000-2009	San Dieguito River Basin	Average	Unknown	Unknown	0.38	Unknown
2000-2009	San Diego River Basin	Average	11.81	0.59	0.61	51.18[b]

a. *Data for the San Dieguito River Basin and the San Diego River Basin were obtained from Flint et al. (2012).*

b. *Date range not provided in Flint et al. (2012)..*

Following this final check on the SWB performance the parameter modifications to the Lake Henshaw Watershed were applied to the remaining three watersheds. The four SWB watershed models were then used to simulate future climate conditions using updated precipitation and climate data, as described in Section 2, while keeping all remaining parameters unchanged. Future conditions included two GCM selections, CMCC-CMS and CanESM2. SWB outputs from the future climate condition scenario simulations were provided as input to the GoldSim model. Parameters provided for use in the GoldSim model included runoff and recharge.

3.4 SWB Model Uncertainty

As discussed in the model description and performance evaluation section above, there are several input parameters and conceptual assumptions that effect the results of the SWB model predictions. Repeat simulations using variations in input parameters are used to both adjust results in the pursuit of history matching to the TODD GW RRR model results and USGS gauge data. The results of these myriad simulations also provide information regarding the sensitivity of the model to assumptions in selecting the input parameters. As described above, the root zone depth parameter was identified as a sensitive parameter and considerable attention was given to selecting an appropriate range of values for root zone depth. This knowledge of sensitivity and evaluation of expected ranges of data variation improve history matching results and help understand uncertainty.

The causes of model uncertainty are dependent upon the nature of the natural system being simulated, the accuracy of the conceptual understanding of that system, and finally on the limitations inherent in the modeling tool. Because surface water and groundwater interactions are not simulated in the SWB code (Westenbroek et al., 2010), the behavior of the natural surface water system as reflected in the USGS gauge data can't be simulated as accurately as would be possible with another modeling approach. In addition, deep percolation (underflow) is not considered in the estimation of recharge in the SWB and cannot be evaluated as contribution to surface water flow, a more downstream location in the watershed. Due to these limitations, underflow to Lake Henshaw was not accounted for in the Lake Henshaw SWB model and the depth from the bottom of the root zone to the top of the water table was also not considered.

The SWB model as constructed is not a unique combination of input parameters that result in an exact match to other evaluations of this watershed (Todd GW, 2018 and Flint et al, 2012) and the available measured data. However, reasonableness checks, careful vetting of selection of input data, and the closeness of runoff predictions to performance comparison data sets provides sufficient confidence in the results to support the use in the GoldSim modeling.

Section 4: GoldSim Model Development

GoldSim is a simulation software used to dynamically model complex systems and was selected and used to create an operational model for the LWS. GoldSim can map out and draw the system with connection data and functions that mimic system operations and support decision making under changing system conditions.

This software was selected as it provided a flexible way to visually represent and operationally mimic the District's LWS. The model allowed for built-in control rules that helped represent changes in operational procedures, including representative changes to infrastructure through various infrastructure investments, such as optimizing the Warner Basin wellfield, mitigating harmful algal blooms (HABs) at Lake Henshaw, and increasing the storage at Lake Wohlford resulting from the future dam replacement. This section describes the development of the GoldSim model. The modeling effort included developing a historical water balance model, a control rules model, and baseline and future conditions models within GoldSim that considered five infrastructure investment scenarios.

4.1 Historical Conditions

The BC modeling team developed a historical conditions GoldSim model to represent the LWS. BC used available observed data as model inputs to reproduce historical conditions and used a water balance analysis to quantify components not explicitly defined by observed data like system losses, stream percolation, and seepage. Available observed data included the historical precipitation data discussed in Section 2 and data provided by the District on observed evaporation, drafts, wellfield production, Rincon releases, and stage-storage-area relationships.

The modeling effort required a thorough understanding of the LWS to develop the existing conditions GoldSim model. A system schematic shown in Figure 4-1 details all system components and their interconnects and was developed through coordination with District staff. The system schematic provided a foundational understanding for GoldSim model development. Components of the LWS modeled in GoldSim are elaborated within this section.

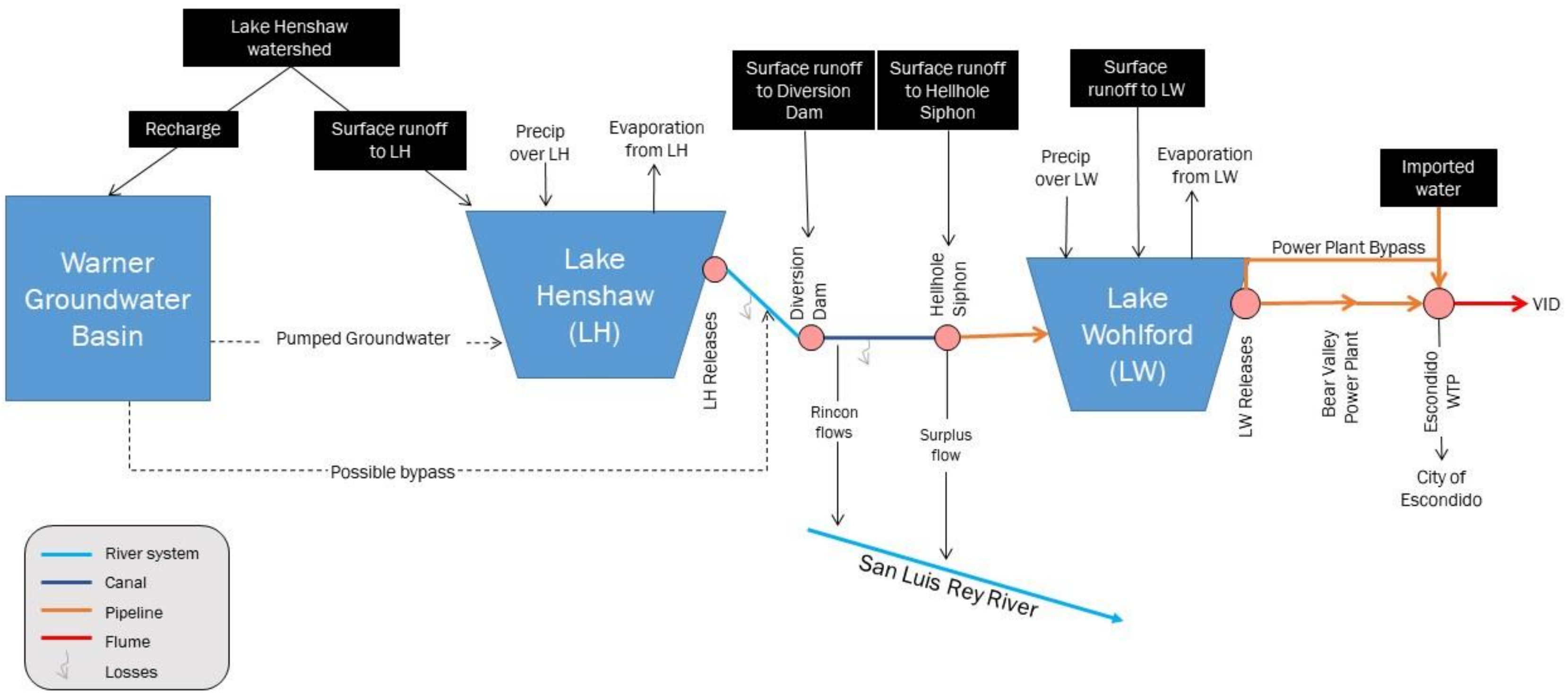

Figure 4-1. System schematic of District's LWS

BC created model elements for the historical conditions GoldSim model to represent the physical system depicted in the system schematic. The model included a Lake Henshaw component, representations of the watersheds for the Intake and Siphon from the SWB models, estimated system losses between Lake Henshaw and the Intake and between the Escondido Canal and Hellhole Siphon, observed Rincon releases, a Lake Wohlford component, and flows to the EVWTP. BC calibrated the model to match observed data and the water balance.

The Lake Henshaw component of the model was comprised of inflows to the lake, storage within the lake, and outflows from the lake as shown in Figure 4-2. The District provided data for numerous Lake Henshaw components including observed monthly time series from 1953 to 2022 for wellfield production, evaporation on the lake, lake storage, and drafts from the lake, as well as data for stage-storage-area relationships in the lake. BC maintained the loss factors developed by Bookman-Edmonston, which assumed 18 percent of wellfield production is lost to evaporation or returned to aquifer along the conveyance ditch (2022).

The Lake Henshaw component used the Lake Henshaw watershed area from the SWB model and SWB outputs for recharge and runoff. The Lake Henshaw component used the observed monthly precipitation time series discussed in Section 2 for both precipitation across the Lake Henshaw watershed and on the lake surface.

Seepage into Lake Henshaw was estimated using the ABCD monthly water balance model developed by Thomas (1981). Seepage represents the net gain from the local aquifer to the lake. The Bookman-Edmonston evaluation (2002) also examined seepage into Lake Henshaw, which helped to inform these estimates. The ABCD model was used to create a relationship between precipitation and seepage into the lake. Percolation losses along streambeds was estimated using regression analysis based on a balance of net percolation from TODD GW and observed precipitation.

Spills from Lake Henshaw were simulated based on simulated storage within the lake, the District-provided maximum volume of the lake (51,700 AF), and the District-provided stage-storage relationships in the lake. The Lake Henshaw component of the model was calibrated to simulate District-provided data for lake storage (1953-2022) and District-provided data for spills (1953-2022). The calibration effort also used a water balance analysis to compare simulated and observed values for the WY average volumes of all Lake Henshaw components (inflows, lake storage, outflows). Simulated values included comparisons to the Bookman-Edmonston study (2002) and TODD GW (2018).

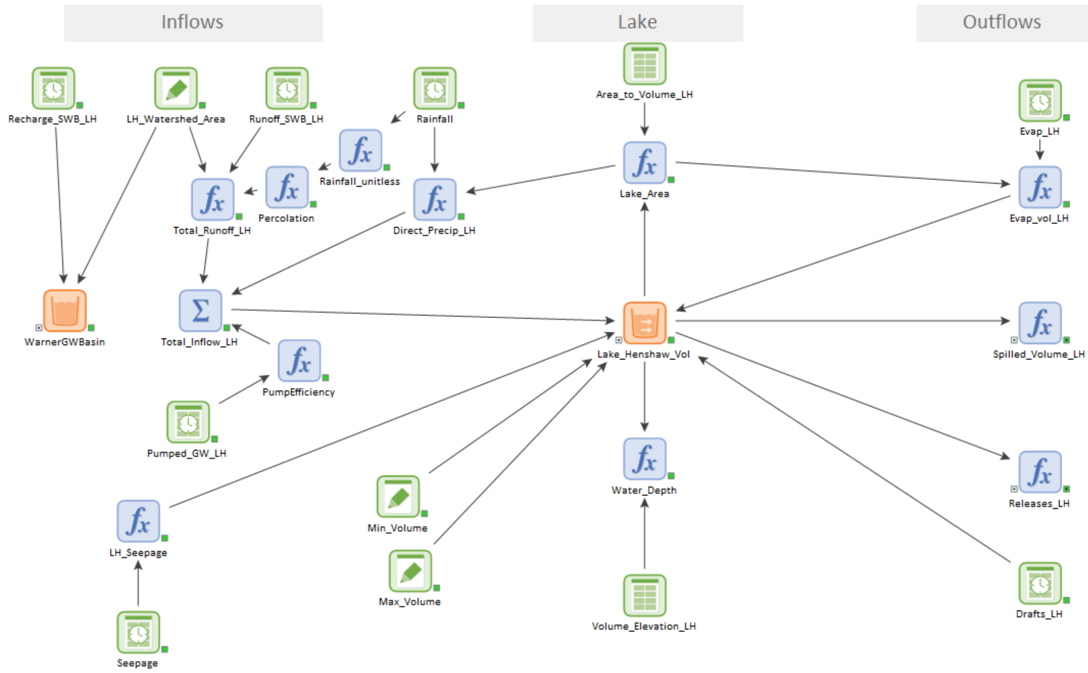

Figure 4-2. Lake Henshaw Component of the Historical Conditions GoldSim Model of VID's LWS

The Lake Henshaw component of the model simulated inflows to downstream components of the model as shown in Figure 4-3. The District provided data for observed monthly time series from 1953 to 2022 for the Rincon releases. The model used the watershed areas from the SWB models and SWB outputs for runoff from the SWB Intake and SWB Siphon watersheds as inflows to the intake to the Escondido Canal and the Hellhole Siphon, respectively. BC assumed that inflows to the Escondido Canal and the Hellhole Siphon were constrained by the canal capacity (3019 AF).

Estimated system losses between Lake Henshaw and the Intake and between the Escondido Canal and Hellhole Siphon were calibration parameters. BC modeled riparian losses between Lake Henshaw and the intake to the Escondido Canal along the San Luis Rey River as a percentage of modeled releases from Lake Henshaw and estimated losses using an iterative approach to approximate the mean, median and range of District-provided observed monthly flows at the Canal Intake gauge from 1953 to 2022. Riparian losses were estimated as one percent of Lake Henshaw releases. BC modeled system losses between the Escondido Canal and Hellhole Siphon as a percentage of modeled flows to the Canal Intake and estimated losses using an iterative approach to approximate the mean, median and range of District-provided observed monthly flows at the Canal Outlet gauge from 1953 to 2022. System losses were estimated as four percent of Canal Intake flows.

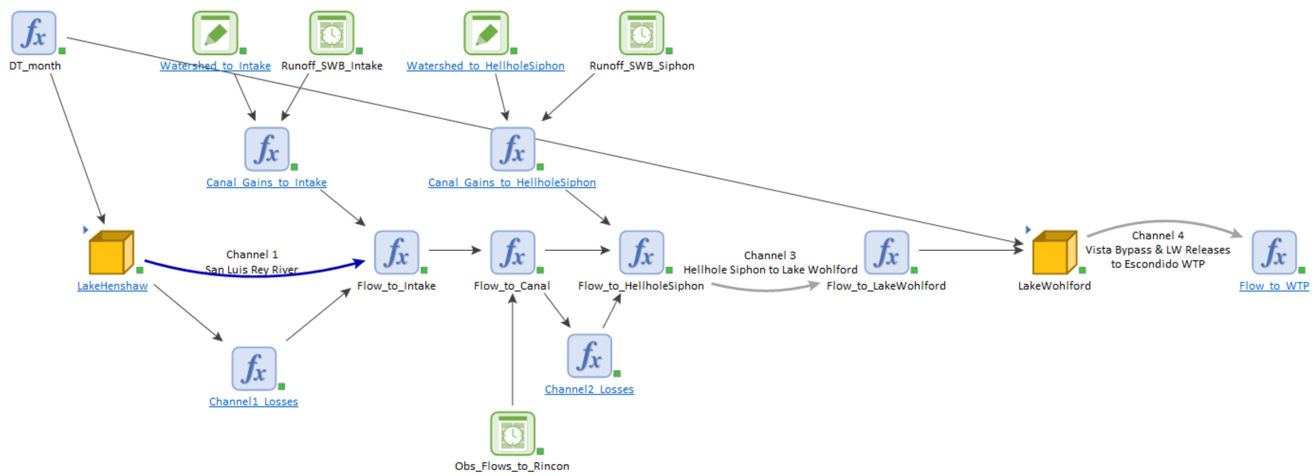

Figure 4-3. Historical Conditions GoldSim Model of VID's LWS

The Lake Wohlford component of the model was comprised of inflows to the lake, storage within the lake, and outflows from the lake as shown in Figure 4-4. The District provided data for numerous Lake Wohlford components including observed monthly time series for flow at the Escondido Canal Outlet (1953-2022) and drafts from the lake (2017-2022), as well as data for stage-storage-area relationships in the lake. BC used the monthly average draft to extend the model time series from 1953 to 2022.

The Lake Wohlford component used the Lake Wohlford watershed area from the SWB model and SWB outputs for runoff. Limited precipitation and evaporation data were available for Lake Wohlford. The Lake Wohlford component used the observed monthly precipitation time series discussed in Section 2 for both precipitation across the Lake Wohlford watershed and on the lake surface. The District-provided evaporation over Lake Henshaw was assumed to be representative of conditions over Lake Wohlford. The Lake Wohlford component of the model was calibrated to simulate District-provided data for lake storage (2017-2022).

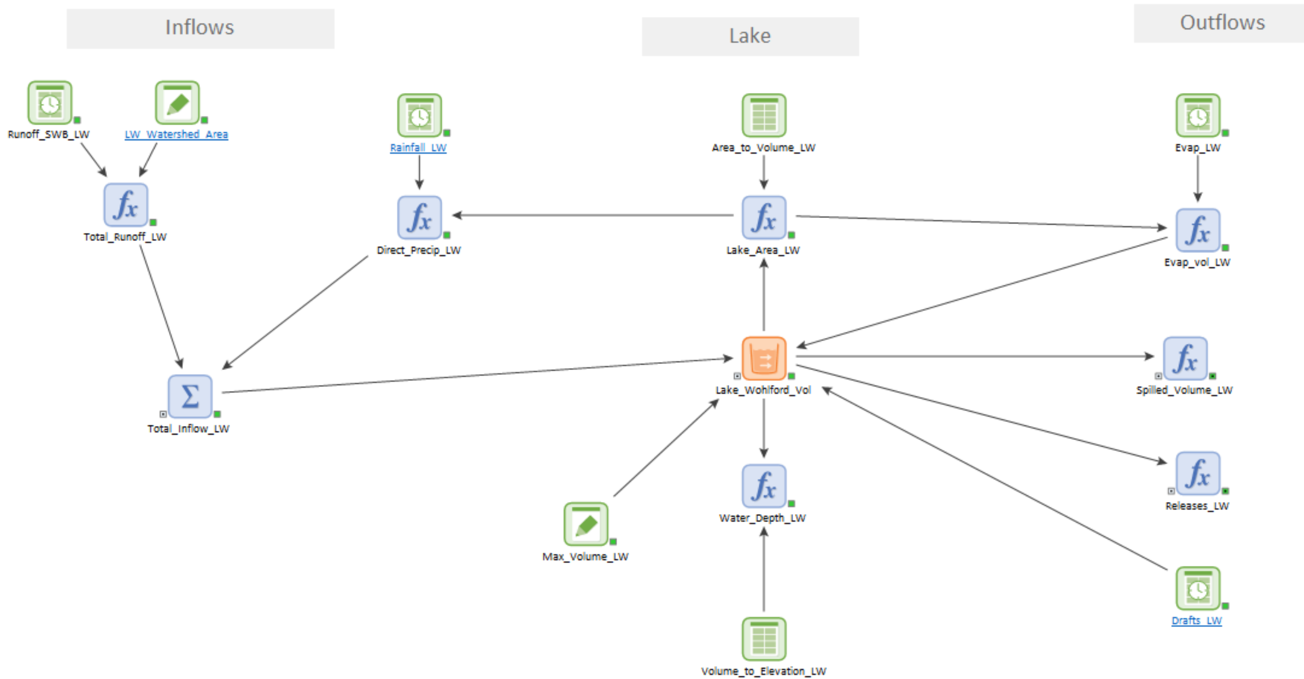

Figure 4-4. Lake Wohlford Component of the Historical Conditions GoldSim Model of VID's LWS

The historical conditions GoldSim model was then modified to include control rules that represented general operating conditions. BC replaced observed time series for wellfield production, outflows from both lakes, and Rincon releases in the GoldSim model with operational logic. This approach allowed BC to use the same control rules for future conditions.

The control rules GoldSim model used information obtained from collaboration and discussion with District staff to develop the operational logic and model responses to refine operational logic. Lake Henshaw drafts were based on a constant release rule value that was iteratively adjusted to match observed water year average draft volumes.

Pumped groundwater was based on assumed operating conditions with eight wells pumping up to 800 gallons per minute for a total of 848 acre-feet (AF) per month when Lake Henshaw storage fell below 15,000 AF.

Rincon releases were modeled as a constant annual demand of 2,900 AF distributed monthly based on the average observed monthly percent released. The constant annual demand value of 2,900 AF represents the average post-settlement volume projected to be released per discussion with the District.

Lake Wohlford releases were assumed equivalent to Lake Wohlford inflows, which neglects the available storage.

Simulated values for all model parameters in the control rules GoldSim model were compared to observed data from the District. The modeling team finalized the control rules GoldSim model once it was able to approximate WY average volumes from District-provided observed data. The comparison to observed data is shown in Figure 4-5.

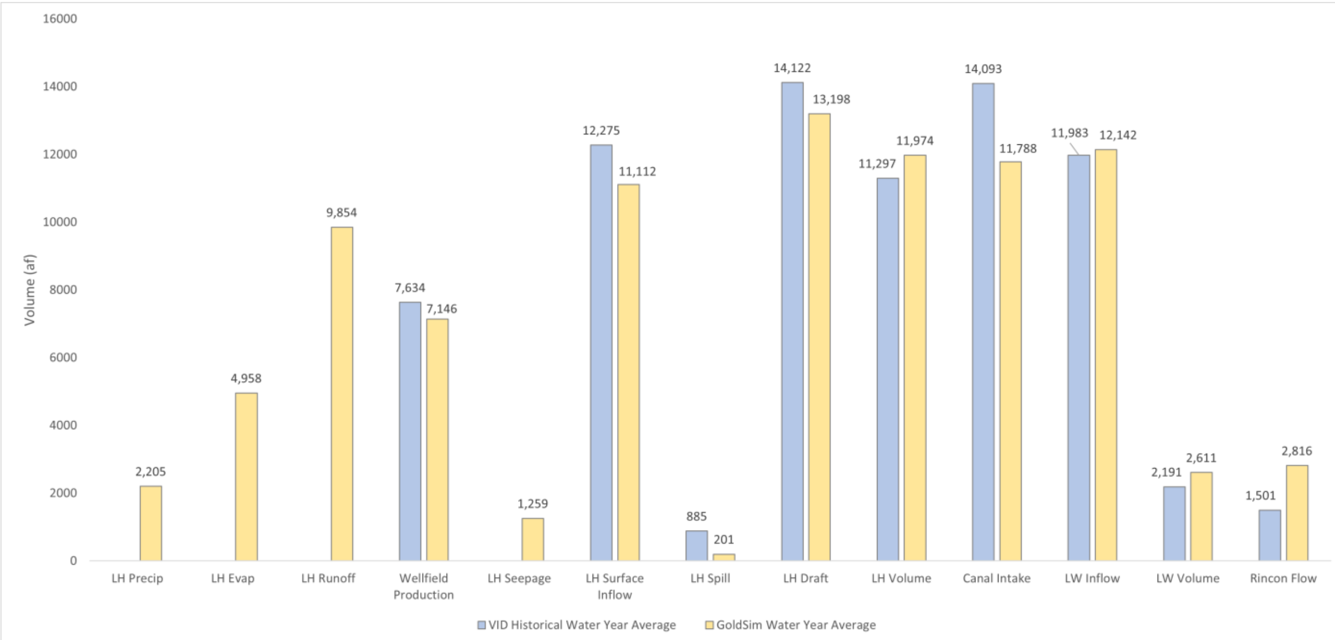

Figure 4-5. Comparison water year average simulated results from control rule GoldSim model to District observations
LH = Lake Henshaw; LW = Lake Wohlford

Once the control rules model was finalized, the baseline model was developed by running the control rules model for the 30-year baseline period from the representative water year 1957 to 1986. The baseline model also replaced the observed evaporation with calculated evaporation using the simplified Penman method. The simplified Penman method used correction factors to match the calculated evaporation with the average monthly observed evaporation at Lake Henshaw. The estimated evaporation time series had a monthly mean of 0.42 ft ± 0.01 ft and the observed data had a monthly mean of 0.39 ft ± 0.01 ft. The simplified Penman method allowed BC to develop evaporation inputs for future conditions using the same method.

4.2 Investment Scenarios

BC used the baseline GoldSim model to calculate the available local yield under five investment scenarios ranging from minimal to substantial upgrades to the LWS. Potential upgrades included in-lake HABs mitigations, an expanded wellfield, and a lake bypass pipeline. The five investment scenarios are defined in Table 4-1.

Table 4-11. Investment Scenarios

Investment Scenario	Description	Wellfield Operational Limitation (AFY)	Average Water Year Wellfield Yield (AFY)
1	Low-range: • Maintain wellfield as-is; no new wellheads • No long-term in-lake HABs solution • Respond to HABs using algaecide when needed • No lake bypass pipeline or additional operational flexibility	5096	--
2	HABs Control Only: • Implement long-term in-lake HABs solution • Preventative HABs control using chemical treatment • No lake bypass pipeline or additional operational flexibility	5096	--
3	Baseline or "Mid-range": • Optimize wellfield to achieve the historical, and can achieve sustainable yield over 12 months • Implement long-term in-lake HABs solution • Preventative HABs control using chemical treatment • No lake bypass pipeline or additional operational flexibility	--	7140
4	Maximum Allowable Sustainable Yield: • Maximize wellfield to achieve allowable sustainable yield • Implement long-term in-lake HABs solution • Preventative HABs control using chemical treatment • No lake bypass pipeline or additional operational flexibility	--	9125
5	High-range: • Maximize wellfield to achieve allowable sustainable yield • Implement long-term in-lake HABs solution. • Preventative HABs control using chemical treatments • Install a lake bypass pipeline for additional operational flexibility	--	9125

AFY = acre-feet per year
LH = Lake Henshaw

BC developed model logic for the five investment scenarios in the GoldSim model. Scenario 1 represented the low-range investment scenario and assumed that the wellfield would be maintained in its current state and that HABs would continue to limit operations. BC modeled the current state of the wellfield using the operational limitation of 5,096 AFY based on discussion with the District. BC assumed the wellfield would operate when Lake Henshaw storage fell below 15,000 AF. BC modeled the impact from HABs by restricting Lake Henshaw releases between June and September. Scenario 1 assumed a value of 1,900 AFY for the

Rincon releases. The volume was released between October through May and distributed across the eight months using the normalized observed monthly percent release. This value represents the recent historical Rincon releases based on communication with the District.

Scenario 2 represented the HABs Control Only investment scenario and assumed that the wellfield would be maintained in its current state; however, this scenario assumed that HABs would no longer limit operations. BC modeled the current state of the wellfield using operational limitation of 5,096 AFY based on discussion with the District. BC assumed the wellfield would operate when Lake Henshaw storage fell below 15,000 AF. Scenario 2 also assumed a value of 1,900 AFY for the Rincon releases; however, the volume was released throughout the year based on the observed monthly percent release.

Scenario 3 represented the mid-range investment scenario and assumed that the wellfield would be improved to achieve the District-provided historical yield of 7,140 AFY. BC modeled the improved wellfield using 8 pumps at a rate of 800 gallons per minute (gpm), which is equivalent to 848 AF per month and was based on discussion with the District. BC assumed the wellfield would operate when Lake Henshaw storage fell below 15,000 AF. Scenario 3 assumed a value of 2,900 AFY for the Rincon releases. The volume was released throughout the year based on the observed monthly percent release. This value represents the post-settlement average projected Rincon releases based on communication with the District.

Scenario 4 represented the maximum allowable sustainable yield investment scenario and assumed that the wellfield would be maximized to achieve the sustainable yield of 9,125 AFY based on the TODD GW study (TODD GW, 2018). BC modeled the maximized wellfield using 10 pumps at a rate of 800 gallons per minute (gpm), which is equivalent to 1,061 AF per month and was based on discussion with the District. BC assumed the wellfield would operate when Lake Henshaw storage fell below 15,000 AF. Scenario 4 assumed a value of 2,900 AFY for the Rincon releases as in Scenario 3.

Scenario 5 represented the high-range investment scenario and assumed that the wellfield would be maximized to achieve the sustainable yield of 9,125 AFY based on the TODD GW study (TODD GW, 2018) and that a bypass would be installed for additional operational flexibility. BC modeled the maximized wellfield using 10 pumps at a rate of 800 gallons per minute (gpm), which is equivalent to 1,061 AF per month and was based on discussion with the District. BC assumed the wellfield would deliver water to Lake Henshaw between October and May when storage fell below 2,500 AF. BC assumed that the bypass would operate between June and September when Lake Henshaw storage fell below 15,000 AF. The wellfield operation logic mimicked the use of stored water during the late fall through early spring rather than pumped groundwater, and the use of groundwater during the summer and early fall to keep lake levels low and minimize evaporative losses. Scenario 5 also assumed a value of 2,900 AFY for the Rincon releases as in Scenarios 3 and 4.

BC estimated the local yield for each investment scenario using the baseline GoldSim model. BC iteratively adjusted a constant monthly release rule from Lake Henshaw to match either the wellfield operational limitations for scenarios 1 and 2, or the average WY wellfield yield for scenarios 3 through 5. The predictive local yield for the District was assumed to be half of the Lake Wohlford releases to reflect agreements with the City of Escondido. The results of the baseline modeling effort are presented in the following section.

The baseline GoldSim model was then used to develop two future condition models based on GCMs representing a dry future and a wet future as described in Section 2.2.4. The baseline GoldSim model, which uses historical data, was viewed as a middle “Baseline” condition, while the climate projections were used to examine lower and upper bounds from the driest to the wettest future climate conditions.

Model elements for seepage, recharge, runoff, precipitation, and evaporation were developed for the dry and wet climate scenarios. The SWB models provided inputs for runoff and recharge as discussed in Section 3.2. BC used a quantile delta mapping process to develop future precipitation time series as discussed in Section 2.2.3. Future evaporation time series were developed using the Simplified Penman method and the correction factors used to match the average monthly observed evaporation at Lake Henshaw. BC determined seepage into Lake Henshaw for the future conditions using the ABCD model and the future conditions precipitation and evaporation time series.

The dry, and wet GoldSim models were expanded to the five possible investment scenarios used to estimate the local yield for future conditions. The District's local yield was assumed to be half of the Lake Wohlford releases. The results of the future conditions modeling effort are presented in the following section.

Section 5: Results

Key Finding: 80 percent of the modeled scenarios estimating future climate conditions project that the District can confidently rely on local water being available over a wide variety of climate conditions. This climate conditions analysis when applied to the economic analysis weighs in favor of the flume replacement project if modest investments are made to the LWS.

Table 5-1 provides the estimated local yield results from the GoldSim model. These numbers represent the District's share of the average annual local yield for each of the five LWS investment scenarios currently being considered by the District. Each of the five investment scenarios was modeled against three climate change scenarios, which applied delta change factors for "Dry" (CMCC_CMS RCP8.5), "Baseline" (Historical), and "Wet" (CanESM2 RCP8.5) climate conditions. This produced a total of 15 model runs that represented the various investment scenarios across a range of climate conditions.

Cells highlighted in red in Table 5-1 represent annual average local yield values that would not economically support the Flume Alignment Replacement project, and therefore do not represent a viable "To Flume" project alternative as discussed in Section 1. Green highlighted cells represent annual average local yield values that do economically support the flume replacement project and its long-term operations. These values do not require any modifications to the EVWTP's current blend limitations of 40:60 local-to-imported raw water ratio.

Table 5-1. Possible Range of Local Water System Investment Scenarios

Local Water System Investment Scenario	Capital Costs [a]	Anticipated Range of Average Annual Local Yield (AFY) [b,c,d] Dry [b,c,d] (CMCC_CMS RCP8.5)	Baseline [b,c,d] (Historical)	Wet [b,c,d] (CanESM2 RCP8.5)
Scenario 1: Low-range	$8M	1,790	2,666	3,880
Scenario 2: HABs Control Only	$13M	2,032	3,282	4,690
Scenario 3: Baseline or "Mid-range"	$23M	5,060	6,575	10,727
Scenario 4: Max. Allowable Sustainable Yield	$37M	5,764	7,319	11,125
Scenario 5: High-range	$57M	7,473	8,450	11,323

a. *Capital costs presented are in 2023 dollars and only include District's share of costs (e.g., 70 percent for wellfield projects and 50 percent for Henshaw projects) based on work performed in the Balance Scale Check-In.*

b. *District's share of the anticipated average annual local yield in AFY estimated for the corresponding modelled scenario.*

c. *The District's share of local yield presented herein are results from the predictive climatological model.*

d. *The anticipated local yield values presented in the table above were the direct output of the GoldSim Model. The anticipated local yield values used in the Economic Balance Scale model, as presented to VID's Board on Dec. 11, 2023, have custom reduction factors applied to them for conservatism. The custom reduction factors were developed using the operational experience and guidance of VID's Water Resources staff to capture long-term uncertainties in local water system operations. The intent was to add more pessimism to the economic analysis, thereby reducing local yield, which resulted in an increased confidence in the resulting recommendation "To Flume".*

e. *Legend:*

Red =Future Flume Replacement project is not economically viable (District LWS yield is less than 2,700 AFY).

Green = Economically viable scenarios that do not require improvements to Lake Wohlford or EVWTP to keep to the 40:60 local-to-imported water blend ratio.

Yellow = Requires improvements to Lake Wohlford or EVWTP to generate local yields, which are more than the current 40:60 local-to-imported water blend ratio limitation.

Cells highlighted in yellow represent an upside in local yield generally not seen by the existing LWS as these cells represent scenarios in which infrastructure investments are made to enable achieving historical wellfield pumping capacity (Scenario 3) or the ability to maximizing the wellfield to pump up to the sustainable yield of the groundwater basin (Scenarios 4 and 5). However, potential local yield values in the yellow cells would exceed the 40:60 local-to-imported water limit. In these cases, modest investments in improving the water quality at Lake Wohlford and the treatability at EVWTP would be required to accept blend ratios above the current limitations. Achieving these higher blend ratios will require significant modifications and capital costs to beneficially use the full local yield. This would require treatability studies and an evaluation at a greater level of detail beyond the current scope of this study.

Section 6: Conclusion

This TM presents the analysis of potential changing climatic conditions on the local yield of the District's LWS. The modeling effort presented supports the *"To Flume"* or *"Not to Flume"* decision by developing a projected range of local yields based on varying climate change factors, and further supports addressing the *"How to Flume"* question by incorporating and modeling the local yield under various infrastructure investment scenarios. Several conclusions can be made based on the findings of this study as follows:

Under drier future conditions:

- Under projected drier future conditions, mitigating HABs through in-lake treatments and chemical solutions will not be sufficient on their own to meet the economic viability threshold. Under these conditions, it is recommended that the District consider undertaking at least well repair and replacements, and some new wells to improve wellfield production and enable reaching maximum sustainable yield over the course of a year (seen in Scenario 3).
- Adding additional wells to maximize wellfield production (Scenario 4) under projected drier future conditions would add greater operational flexibility for the District as it is assumed this level of investment would enable the District to withdraw the maximum sustainable yield over the course of a six-month period.

Under baseline future conditions:

- Scenario 1 does not meet the economic viability threshold in the case of baseline future conditions. This implies that a low-range investment may not be sufficient for future infrastructure investments and would still leave the District more vulnerable to potential HABs disruptions.
- Baseline condition results also indicate the favorability of including HABs mitigations activities (both for in-lake treatments and chemical solutions), as these investments support the economic viability of both Scenarios 2 and 3.

Under wetter future conditions:

- Both Scenario 1 (which reflects algicide treatments as-needed, but no new wells nor HABs mitigations) and Scenario 2 (which includes repairing and replacing wells as-needed to maintain historical yield) would still maintain economically viable local yields under projected wetter future conditions. However, the threshold for economic viability is not met for these scenarios under projected drier future conditions.
- Future wetter conditions indicate that investments in wellfield pumping capacity to achieve maximum sustainable yield may require additional investments in treatment system modifications at EVWTP if the District would like to realize the benefit of local yield exceeding the 40:60 local-to-imported water blend ration limitation.

Under all projected future conditions:

- Addressing HABs at Lake Henshaw through in-lake treatments and chemical solutions and optimizing the Warner Basin wellfield remain a priority to enable local yields that meet or exceed the economic viability threshold of 2,700 AFY. This is the case under dry, baseline, and wet future climate conditions.
- Implementing the high-range investment Scenario 5 would require additional investments in treatment system modifications (beyond the current investments listed in this scenario) to fully realize the full

benefit of this additional yield. This is because the local yield across all future conditions in this scenario is estimated to exceed the EVWTP's current 40:60 local-to-imported water blend ratio limitation.

This study recommends considering the full range of potential future climate conditions for the District's planning decisions and infrastructure investments. Given the results of the predictive modeling analysis, the study suggests that the District consider prioritizing Scenario 3 as a potential investment scenario as this scenario maintains economic viability with both drier and baseline future climate conditions. In a wetter future condition, however, improvements may need to be made to the EVWTP treatment system to enable realization of additional local yield. It is recommended that future source water quality testing and treatability analysis be performed to assess and quantify the need for EVWTP improvements under high blend ratios.

Overall, results of this study indicate that the anticipated range of local yield across dry, baseline, and wet projected future climate conditions represent a significant number of conditions that meet or exceed the economic viability threshold for the "To Flume" decision. In applying this analysis to the Balance Scale Check-In, this study provides support weighing in favor of a "To Flume" project if modest investments are made to the LWS.

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