Desert Research Institute

Addressing Basin Management Objectives for the Tahoe Valley South (TVS – 6.5.01) Groundwater Basin

Greg Pohll
Seshadri Rajagopal
Rosemary Carroll
Susan Rybarski

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Prepared by
Desert Research Institute, Reno, Nevada

Prepared for
South Tahoe Public Utility District

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EXECUTIVE SUMMARY

The South Tahoe Public Utility District ("District") developed an updated Groundwater Management Plan (GWMP) for the Tahoe Valley South Subbasin (6-5.01) (Kennedy-Jenks, 2014). The GWMP identified eight Basin Management Objectives (BMOs) to effectively manage the groundwater resource. Many of these objectives required additional analysis of the hydrologic system using recently developed hydrologic modeling tools developed by the Desert Research Institute (DRI) (Carroll, *et al.*, 2016a; Carroll *et al.*, 2016b). This report details responses for five of the BMOs outlined in the GWMP.

BMO #7, Action 3 outlined the need for hydrologic modeling tools within the TVS basin. Sophisticated numerical modeling tools have been developed to assess the hydrologic conditions within the TVS Basin. The modeling framework improves water balance estimates of precipitation, streamflow, evapotranspiration, mountain-front recharge, infiltration, and groundwater flow. The models provide a quantitative tool for evaluating future conditions as well as furthering the overall hydrogeological understanding of groundwater conditions in the TVS Basin.

BMO #4, Action #2 outlined the need to identify recharge areas, amounts, and capture zones for municipal wells. The hydrologic models determined that most of the recharge occurs in the Crystal Range (west of Lake Tahoe) of the Sierra Nevada and Carson Range. Annual recharge ranges from 9 inches in the valley to upwards of 34 inches in the higher elevations. Groundwater recharge is largely dependent on annual precipitation and a regression equation was developed between annual precipitation at Hagan's Meadows climate station to groundwater recharge. Average annual recharge over the entire simulation period (1983– 2015) is 39,000 AFY. Steady-state and time-dependent (2, 5, 10, and 20 years) capture zones were created for the 15 active water supply wells.

BMO #5, Action 1 outlined the need to determine the effects groundwater pumping on surface water. A baseflow depletion analysis was performed for local streams and Lake Tahoe separately over the simulation period 1983 – 2015. As pumping increased in the 1980s, baseflow depletion rates for Lake Tahoe steadily increased from just under a 1000 AFY in 1983 to an average of 5,900 AFY from 2000 – 2015. The depletion rates for streams steadily increased from a few hundred AFY in 1983 to an average of 2,500 AFY from 2000 – 2015. Following 2000, the baseflow reduction from streams represents 2 percent of the average annual runoff (124,000 AFY). Capture maps from Lake Tahoe and streams were created. Results revealed two areas where the sources of water withdrawal are different. North of the Lake Tahoe Airport, most of water withdrawal is from Lake Tahoe. South of the South Lake Tahoe Airport, most of water withdrawal is from streams. We are recommending that pumping rates do not exceed 12,400 AFY south of the airport to ensure that stream ecology is not harmed, but this threshold is well below current groundwater extractions (1,200 AFY) and the current allocations for the District (9,528 AFY).

BMO #5, Action 3 outlined the need to evaluate the impacts of climate change. Six climate scenarios were developed using global climate models (CMIP5) and a historically-based drought scenario to assess the impact of a changing climate on the TVS Basin. They include drier with less warming, drier with more warming, wetter with more warming, wetter with less warming, warming only with no change in future precipitation, and a 12 year drought scenario. The two wetter scenarios resulted in groundwater recharge rates 24 and 34 percent larger than baseline conditions for the wet/hot and wet/warm scenarios, respectively. The dryer scenarios led to less recharge of 24 and 32 percent less than baseline, for the dry/hot and dry/warm scenarios, respectively. Increasing temperatures without changing precipitation led to 5 percent less recharge as compared to baseline conditions. The drought scenario resulted in 32 percent

less recharge. The dry/hot scenario resulted in the largest water level declines with most regions experiencing declines of 0 – 10 feet over small areas in the south and southeast with declines just over 10 feet. The TVS Basin will remain in a sustainable condition for all of the climate scenarios investigated so no additional management activities are required at this time beyond ongoing monitoring. Beyond ongoing monitoring, additional research on the impacts of climate change on the groundwater resources in the TVS Basin is not needed until CO_2 emissions far exceed those being predicted in RCP 8.5 (worst case).

BMO #7, Action 4 outlined the need to develop a monitoring network. Two areas were identified as needing additional groundwater monitoring beyond the existing semiannual monitoring. Additional monitoring is needed in the area just north of the South Y to monitor localized drawdown effects from wells not controlled by the District and to more thoroughly monitor the PCE contaminant plume in this region. A PCE monitoring plan should be developed in conjunction with the ongoing feasibility study of remedial alternatives to mitigate the regional South “Y” Plume. Though less critical, additional monitoring in the southeast would help identify potential groundwater level changes due to climate change.

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LIST OF ACRONYMS

ABC	Analysis of Basin Conditions
AFY	Acre-Feet per Year
BMO	Basin Management Objectives
CCTAG	Climate Change Technical Advisory Group
CMIP5	Coupled Model Intercomparison Project phase 5
CSLT	City of South Lake Tahoe
DDW	California Department of Drinking Water
DEM	Digital Elevation Model
District	South Tahoe Public Utility District
DRI	Desert Research Institute
DWR	California Department of Water Resources
ET	Evapotranspiration
GCM	Global Climate Model
GSFLOW	Groundwater and Surface water Flow
GSFRM	GSFLOW Regional Model
GSP	Groundwater Sustainability Plan
GWMP	Groundwater Management Plan
HPC	High-Performance Computing
LRWQCB	Lahontan Regional Water Quality Control Board
LULC	USGS land use land cover
MNW2	Multi-Node Well
MODFLOW	USGS Modular Groundwater Flow model
NED	National Elevation Dataset
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PRMS	Precipitation-Runoff Modeling System
RCPs	Representative Concentration Pathways
SGMA	Sustainable Groundwater Management Act
SNOTEL	Snow Telemetry
STATSGO	State Soil Geographic
SWRCB	California State Water Resources Control Board
TRPA	Tahoe Regional Planning Agency
TVN	Tahoe Valley North
TVS	Tahoe Valley South
TVW	Tahoe Valley West
UPW	Upstream Weighted
USGS	U.S. Geological Survey
W/m^2	Watts per square meter
WCRP's	World Climate Research Programme's
WEL	Traditional Well

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1.0 INTRODUCTION

The South Tahoe Public Utility District ("District") developed an updated Groundwater Management Plan (GWMP) for the Tahoe Valley South Subbasin (6-5.01) (Kennedy-Jenks, 2014), herein referred to as the TVS Basin. The GWMP identified eight Basin Management Objectives (BMOs) to effectively manage the groundwater resource. Many of these objectives required additional analysis of the hydrologic system using recently developed hydrologic modeling tools developed by the Desert Research Institute (DRI) (Carroll, *et al.*, 2016a; Carroll *et al.*, 2016b).

The Tahoe Valley South groundwater model framework was used to address five BMOs as outlined below:

- BMO #7, Action 3 – Develop hydrologic modeling tools
- BMO #4, Action 2 – Delineate recharge areas
- BMO #5, Action 1 – Determine pumping effects on surface water
- BMO #5, Action 3 – Determine the impacts of climate change
- BMO #7, Action 4 – Develop a monitoring network

By design, this project developed sophisticated numerical modeling tools that are now being used by local stakeholders to answer a variety of hydrologic questions. The modeling framework improves water balance estimates of precipitation, streamflow, evapotranspiration, mountain-front recharge, infiltration, and the associated interactions amongst all these processes. The models provide a quantitative tool for evaluating future conditions as well as furthering the overall hydrogeological understanding of groundwater conditions in the TVS Basin.

At outlined in BMO #4, Action 2, a regional groundwater vulnerability assessment is needed to evaluate the entire TVS Basin to determine areas where the aquifer is susceptible to contamination from surface activities (Kennedy-Jenks, 2014). The spatial and temporal distribution of groundwater recharge is explicitly calculated within the modeling framework and these data were used to develop maps showing groundwater recharge amounts over time and for specific time periods. In addition, the models were used to calculate steady-state and time-dependent capture zones for active municipal wells within the TVS Basin.

Operation of water supply systems has the potential to effect environmental conditions, primarily through the lowering of groundwater levels (Kennedy-Jenks, 2014). Environmental habitats that could be affected include lakes, streams and wetlands. The hydrologic models were used to ascertain whether groundwater withdrawals from local wells have a substantial effect on surface water bodies. Two types of calculations were done to address BMO #5, Action 1. First, the model simulated groundwater levels with and without pumping at individual wells to determine the reduction in groundwater flows to surface water over time. The second approach used the model to produce maps of surface water depletion within the TVS Basin. These maps are referred to as "capture maps" and they are useful for illustrating the effects of pumping locations on surface water depletion within a large set of possible pumping locations within an aquifer (Leake *et al.*, 2010).

The impacts of climate change (BMO #7, Action 4) were addressed by developing a suite of locally downscaled global climate model (GCM) simulations for temperature and precipitation using a recently developed guidance document (Lynn, 2015) developed by the Climate Change Technical

Advisory Group (CCTAG) that was empaneled by the California Department of Water Resources (DWR). Five GCM based scenarios were developed that include a full range of potential climate conditions: 1) hotter and drier, 2) hotter and wetter, 3) warmer and drier, 4) warmer and wetter, and 5) warmer but no change in precipitation. One additional climate scenario was developed to test an extreme drought scenario because GCMs may not effectively represent meteorologically realistic extreme climate scenarios. These climate forcings were used within the hydrologic modeling framework to assess changes in groundwater recharge and associated impacts to groundwater levels and storage. In addition, we respond to a recently developed whitepaper (Christian-Smith, 2017) that evaluated the climate change approach described in the Analysis of Basin Conditions report for the TVS Basin (Pohll *et al.,* 2016).

BMO #7, Action 4 was identified so the District could reevaluate its groundwater monitoring network to improve the ability to track changes in groundwater levels and quality in the TVS Basin. The modeling framework was used to highlight areas that may experience increased drawdown rates under a changing climate. Groundwater storage changes within the TVS Basin were created and maps that show areas of potential drawdown and locations of existing monitoring wells to determine additional locations where monitoring is valuable.

1.1 ANALYSIS AREA

The TVS Basin is part of the larger Tahoe Valley Groundwater Basin, which is located within the Lake Tahoe Hydrologic Basin and incorporates the sediment-filled basins bordering Lake Tahoe. The Tahoe Valley Groundwater Basin is subdivided into three subbasins: TVS, Tahoe Valley West (TVW), and Tahoe Valley North (TVN) as shown in Figure 1. Of these three subbasins, the TVS Basin is the largest and most productive.

The BMO Analysis covers the entire TVS Basin, and the surrounding watersheds that contribute groundwater flow to the TVS Basin (Figure 2). From the TVS Basin's western boundary, the analysis area further extends to include the watersheds that flow into Emerald Bay, Cascade Lake and Fallen Leaf Lake, as well as the Camp Richardson Watershed abutting Lake Tahoe. In the southwest and southern regions, the Tallac Creek, Taylor Creek, and Upper Truckee Watersheds are included. In the east, Trout Creek, Bijou Creek, and Bijou Park Watersheds extend to the California/Nevada state line. The Edgewood Creek and Burke Creek watersheds in Nevada are also included because groundwater from these areas flows into the TVS Basin (Figure 2).

The TVS Basin has an area of approximately 23 square miles (14,814 acres) in El Dorado County, California (Figure 2). The TVS Basin is roughly triangular in aerial extent and is bounded on the southwest by the Sierra Nevada, on the southeast by the Carson Range, and on the north by the southern shore of Lake Tahoe. The Basin generally conforms to the valleys of the Upper Truckee River and Trout Creek. The TVS Basin does not share a boundary with any other DWR basin or subbasin. The City of South Lake Tahoe (CSLT) overlies the northern portion of the TVS Basin. The southern boundary extends about three miles south of the town of Meyers. The northeast boundary of the TVS Basin is defined by the California-Nevada state line.

Elevations within the TVS Basin range from 6,225 feet at lake level, rising to above 6,500 feet (Figure 3). Elevations extend above 10,000 feet within the analysis area along the Carson Range and Sierra Nevada. Portions of seven watersheds overlie the TVS Basin, the largest of which include the Upper Truckee River. The Upper Truckee River flows north across the entire length of the basin and drains into

Lake Tahoe through the Upper Truckee Marsh. The Upper Truckee River is joined by Grass Lake and Big Meadow Creeks along the southern extent of its course, Angora Creek centrally, and Trout Creek near Lake Tahoe (Figure 3).

2.0 BMO #7, ACTION 3 – HYDROLOGIC MODELING TOOLS

Two hydrologic models were developed by DRI for the analysis area 1) groundwater flow model using MODFLOW-NWT and 2) a fully coupled surface and groundwater model using GSFLOW. These models are detailed in two reports (Carroll, *et al.*, 2016a; Carroll *et al.*, 2016b) and briefly described below. In addition to addressing BMO #7, Action 3, the models are being made available to local stakeholders including the District, Tahoe Regional Planning Agency (TRPA), Lahontan Regional Water Quality Control Board (LRWQCB), and El Dorado County.

The MODFLOW-NWT model is referred to as the TVS groundwater model. The model is used to quantify the TVS Basin conditions and is based on the U.S. Geological Survey (USGS) MODFLOW-NWT (Niswonger *et al.*, 2011) software. MODFLOW-NWT is the latest installment of the USGS modular program and relies on the Newton solution method and an unstructured, asymmetric matrix solver to calculate groundwater head. MODFLOW-NWT is specifically designed to work with the upstream weighted (UPW) package to solve complex, unconfined groundwater flow simulations to maintain numerical stability during the wetting and drying of model cells.

The model grid is oriented north-south and contains 342 rows and 251 columns. Horizontal cell size is 100 meters (328 feet) and is based on the need to capture steep topography, narrow canyons and potentially steep hydrologic gradients. The model is subdivided into four subsurface layers to maintain reasonable computation time. Layers are determined based on production well screen intervals. Land surface elevations are based on 30 meter (98 feet) Digital Elevation Model (DEM) aggregated to a 100 meter (328 feet) resolution. Layer thicknesses are 40 meters (131 ft) for layer 1 and layer 2, and 100 meters (328 feet) for layer 3. Layer 4 bottom elevation is set to a constant 1,600 meters (5,248 feet) to produce variable thickness ranging from approximately 114 meters (274 feet) along the northern boundary with Lake Tahoe to 1,300 meters (4,264 feet) at watershed divides.

The baseline groundwater model simulates two distinct time periods. The first represents steady-state conditions prior to any significant groundwater production in the basin. Hydraulic conductivity was calibrated using the steady-state model configuration. The transient model simulates the period 1983-2015 to calculate changes in groundwater levels and flux due to variations in climate and groundwater extractions. Other time periods are simulated separately and are described in more detail below.

A second model was developed to simulate surface and subsurface hydrologic processes for the entire Lake Tahoe Basin and was used to calculate groundwater recharge. This model was developed by the DRI as part of a U.S. Department of Interior study looking at the historical and future water supply in the Truckee River Basin. The DRI model uses the numeric code Groundwater and Surface water Flow (GSFLOW, Markstrom *et al.*, 2008) which combines the USGS Precipitation-Runoff Modeling System (PRMS, Leavesley *et al.*, 2005) with the USGS Modular Groundwater Flow model (MODFLOW, Harbaugh 2005; Niswonger *et al.*, 2011). GSFLOW estimates energy and water budget partitioning to account for flow within and between the plant canopy and soil zone, streams and the groundwater, and is used to understand effects of climate change on the hydrology of mountain catchments to Lake Tahoe. This model is generally referred to as the GSFLOW Regional Model (GSFRM).

For calculations of recharge, the GSFRM is parameterized from the National Elevation Dataset (NED), State Soil Geographic (STATSGO) soils database, and USGS land use land cover (LULC) dataset. The depth of the root or soil zone is determined by the LULC for each 300 meter grid. Five categories of LULC are used in each 300 meter grid-cell based on dominant vegetation category: bare soils, grasses, shrubs, trees, and water. The GSFRM simulates transient conditions from 1980 to 2015. Daily weather data from four Snow Telemetry (SNOTEL) sites (Echo Peak, Fallen Leaf Lake, Hagans Meadow and Heavenly Valley) are used to drive the model in the region of the TVS Basin. While stations give point climate, Parameter-elevation Regressions on Independent Slopes Model (PRISM) (PRISM Climate Group, 2016) data are used to distribute precipitation spatially over the entire basin. The four climate stations within the basin capture the gradient in precipitation from the west to the east side of the basin. This gradient is especially visible in wet and dry years, when the east side receives far less precipitation compared to the west side in dry years.

A two-year warm-up period is used to remove the influence of initial conditions. Typically, the state of the system is unknown at the start of the simulation and hence a warm-up period is prescribed to avoid the initial state from affecting the simulation. There is no universal prescription in the literature on what this warm-period should be, but examples include a three-year initialization (Fulton *et al.*, 2015), Carroll *et al.*, (2016) used a ten-year spin-up, Ajami *et al.*, (2015) recommends a 11 to 16-year spin-up and Huntington and Niswonger (2012) used a 1-year spin-up. In this study we used a two-year spin-up. For this spin-up period we used observed hydro-meteorological data in Tahoe for the water year 1981-1982. Since, the observations of streamflow matched the simulated flows well for a period independent of the spin-up we deemed the initial spin-up to be adequate.

3.0 BMO #4, ACTION #2 – DELINEATE RECHARGE AREAS

3.1 CURRENT GROUNDWATER RECHARGE

Groundwater recharge was extracted from the GSFRM. Recharge is defined as the model computed excess water leaving the unsaturated root or soil zone and entering the saturated zone after accounting for abstractions of interception, sublimation, surface runoff and evapotranspiration. GSFLOW simulated recharge varies from year to year based on spatial and temporal variations in precipitation. The spatial distribution of groundwater recharge for WY 2010, which represents average precipitation conditions, is shown in Figure 4. Most of the recharge occurs in the mountains of the Sierra Nevada and Carson Range. Annual recharge ranges from 9 inches in the valley to upwards of 34 inches in the higher elevations. This result is consistent with observations of stable isotope levels in stream baseflow and of groundwater from numerous shallow and deep-screened wells which indicate that a significant fraction of groundwater present within the TVS Basin is sourced from precipitation in high elevation areas that recharges at the mountain front and/or in the mountain block (Fogg, *et al.*, 2007). Fallen Leaf and Cascade Lakes are simulated as lakes and therefore receive constant recharge of approximately 30 inches per year.

Groundwater recharge is largely dependent on annual precipitation. A regression equation was developed between annual precipitation at Hagan's Meadows climate station to groundwater recharge (Figure 5) with an R^2 of 0.92. Hagan's Meadow climate station was chosen because it resulted in the best correlation between precipitation at one station versus groundwater recharge. Annual groundwater recharge was derived from the groundwater flow model.

Groundwater recharge from WY 1983 – 2015 is shown in Figure 6. Average annual recharge over the last decade (2006 – 2015) is 36,400 acre-feet per year (AFY) and the average over the entire simulation period (1983– 2015) is 39,000 AFY.

The ratio of recharge computed by the GSFLOW model to annual precipitation, which is termed as “recharge efficiency,” can be used to describe the fraction (or percentage) of precipitation that is converted to recharge. Mean estimated precipitation by GSFLOW for the TVS domain is approximately 344,000 AFY over the hydrologic analysis area. Computed recharge efficiency for the TVS hydrologic basin varies annually but on average (1983 – 2015) is approximately 11 percent. The fraction of precipitation that becomes recharge is consistent with other studies in the region (Flint and Flint, 2007).

3.2 CAPTURE ZONES

Time-dependent capture zones were calculated for 16 active water supply wells within the TVS Basin. The calculated capture zones represent a surface projection of the capture area that ultimately enters a pumping well within a given time period. Time-dependent capture zones represent the intermediate time (e.g. 2, 5, 10, and 20 years) period between the well and an area up-gradient for which water flows to a well in the specified time period. A steady-state capture zone represents the complete flow path from recharge to intake at a well. The amount of time represented by a complete (steady-state) flow path depends on the rate of groundwater movement adjacent to the well. In some wells the complete flow path is realized in 5 years, while in others it is well over 20 years.

The TVS groundwater flow model was used for this analysis but the transient model was converted to steady-state to represent future conditions. A steady-state flow model keeps all model stresses constant for the duration of the simulation. All model parameters are identical to the transient model but pumping rates were averaged over the 2009 – 2016 period. The pumping rates for the 16 large capacity wells included in the simulation are shown in Table 1.

The MODFLOW model calculates groundwater levels and cell-by-cell fluid volumetric flow rates, and MODPATH (Pollock, 2016) is used to calculate the advective particle paths from active wells to a recharge source or another external boundary condition (e.g. Lake Tahoe or stream).

MODPATH calculates time-dependent capture zones by applying a reverse particle tracking algorithm. An effective porosity is required to convert the volumetric flow rates calculated by MODFLOW to advective velocities. An effective porosity of 0.10 was used in the analysis which is consistent with the value used in a PCE transport modeling study near the South Y intersection.

Time-dependent (2, 5, 10, 20 years, and steady-state) capture zones for each well are shown in Figure 7. The flowpath geometry is controlled by the transmissivity (hydraulic conductivity and aquifer thickness), hydraulic head gradient, and pumping rate. Capture zone width increases with increased pumping rate, decreased transmissivity, and increases in hydraulic gradient. Though the Bayview well has the largest pumping rate (2,777 AFY), the capture width is relatively small because the capture zone intersects Lake Tahoe. Al Tahoe #2 is in an area of high hydraulic gradient because of interference with the Bayview well. The Valhalla well abuts lower permeable bedrock which tends to broaden the capture zone. Helen #2 is in a localized area of lower permeable sediments which cause a broader capture zone. The other wells tend to have narrow capture zones which is a due to either lower pumping rates, higher transmissivity, or small hydraulic gradient.

It is important to note that contaminant migration into individual wells may be derived from a larger area than is depicted on Figure 7. The differences can be due to variable pumping rates and dispersion effects. Variable pumping rates, especially changes in relative pumping rates from well to well will cause local head gradients to change spatially and temporally which causes the plume to migrate over larger regions than is simulated with a constant pumping rate. Dispersion effects cause additional contaminant spreading due to spatial heterogeneities and diffusional processes.

Another factor to consider is that local scale heterogeneities are not necessarily included in this regional model. Local features such as clay lenses can cause significant deviations in the flow field which may not be captured in the regional model.

4.0 BMO #5, ACTION 1 PUMPING EFFECTS ON SURFACE WATER

4.1 HISTORICAL EFFECTS OF PUMPING ON SURFACE WATER

Impacts to surface water were quantified using the capture analysis technique developed by Leake, *et al.*, 2010. The method relies on the TVS groundwater model to calculate groundwater flux with and without groundwater pumping. Groundwater flux is the rate of groundwater flow per unit area of a porous media, measured perpendicular to the direction of flow. The change in the flux to or from the surface water body can be attributed to groundwater pumping and this amount is referred to as depletion.

The depletion analysis for Lake Tahoe is provided in Figure 8. As pumping increased in the 1980s, depletion rates to Lake Tahoe steadily increased from just under a 1,000 AFY in 1983 to an average of 5,900 AFY from 2000 – 2015. Following 2000, the groundwater flux reduction to Lake Tahoe represents 50 percent of the pre-development flux (11,700 AFY). It is important to note that the Bayview well, which is located a quarter mile from Lake Tahoe was put into production in 2007 and has been used a lead well with a majority of the groundwater extracted from the TVS Basin being pumped from this well. Prior to significant groundwater pumping groundwater only flowed to Lake Tahoe and flow reversals did not occur. By approximately 1995, flow reversals begin to occur during summer months such that Lake Tahoe acts as a source of water to the aquifer.

The depletion analysis for streams is provided in Figure 9. The depletion rates for streams began to steadily increase from a few hundred AFY in 1983 to an average of 2,500 AFY from 2000 – 2015. Following 2000, the baseflow reduction represents 2 percent of the average annual runoff (124,000 AFY). It is important to note that under pumping conditions groundwater continues to discharge to streams. In other words, groundwater pumping does not draw water from streams but it simply reduces the rate that groundwater flows to streams.

The impact of groundwater pumping on groundwater storage change is shown in Figure 10. The plot shows the difference in groundwater storage change between the groundwater pumping scenario and the no pumping scenario. Positive values indicate that more groundwater is derived from storage under the pumping scenario. Groundwater storage depletion is on the order of 3,000 AFY in the early 1980s as pumping increases and then gradually decreases to near zero as the aquifer achieves a new equilibrium condition. This is a well-known response as groundwater is extracted from an aquifer system. At early time groundwater pumping is primarily derived from storage depletions followed by a transition to other sources such as streams and lakes.

4.2 CAPTURE MAPS

This study adopts the Leake *et al.*, 2010 method to construct surface water capture maps using the TVS Basin groundwater model. The effects of groundwater withdrawals can spread to connected streams, lakes, and wetlands through decreased rates of discharge from the aquifer to these surface-water features. In some settings, increased rates of aquifer recharge also can occur in response to pumping, including recharge from the connected surface-water features. Pumping-induced increased inflow to and decreased outflow from an aquifer is called "streamflow depletion" or "capture." (Barlow and Leake, 2012).

To compute capture fractions, the first step is to calculate water budget components using a groundwater model without a hypothetical water withdrawal well. The second step is to re-run the simulation with a hypothetical water withdrawal well using the same groundwater model as in Step 1 and re-calculate water budget components. The third step is to compute changes in water budget components from Step 1 and Step 2. This process is repeated for hypothetical wells at every grid cell within the TVS groundwater basin (see Figure 11).

The capture value at a specific point is calculated as the ratio of the change in flux for a specific surface water feature (e.g. Lake Tahoe or streams) and the amount extracted at the hypothetical well location. Therefore, the capture values are relative to the pumping rate and range between 0 and 1. These capture fractions are then plotted for all points within the TVS Basin.

The steady-state TVS groundwater model developed for the advective particle path analysis was also used for the surface water capture analysis. All model parameters are identical to the transient model but pumping rates were averaged over the 2009 – 2016 period. The pumping rates for the 16 large capacity wells included in the simulation are shown in Table 1.

The capture analysis represents “steady-state” conditions that occur after the aquifer comes into equilibrium with the pumping rates. Based on the historical results of capture presented in Section 4.1 equilibrium conditions occur after approximately 15 years (see Figures 8 and 9). Thereafter, small changes in pumping rates cause small changes in capture. Therefore, the capture analysis presented herein represents capture conditions for 2017 and beyond.

For complex groundwater models that have high number of grid cells and long model run time, conducting capture calculations may be time-consuming due to prohibitive computational cost. As groundwater model simulations are independent, this study resolves this computational issue by simultaneously running multiple model simulations in a high-performance computing (HPC) cluster using an embarrassingly parallel master/slave technique. The embarrassingly parallel master/slave technique treats the individual solutions as explicit tasks that do not communicate with each other, and assigns each task to a processor. Thus, embarrassingly parallel problems are the easiest to parallelize and have negligible parallelization overhead efficiency (Elshall *et al.*, 2015).

Although the capture analysis requires significant computation resources, it only has to be done once. The capture maps developed are a function of the hydraulic properties of the aquifer and the geometric configuration of the basin. The analysis is not overly sensitive to pumping rates and does not have to be updated if pumping conditions change.

Pumping locations were considered at every active model cells in the TVS groundwater basin, requiring 26,936 model runs. The Multi-Node Well (MNW2) package was used to simulate water withdrawal from a new pumping well as was done with the base model. This package was selected as it showed better model convergence than the traditional well (WEL) package. The pumping rate was set to 100 m^3/day (3,531 ft^3/day) for each hypothetical water withdrawal well. Though the applied rate is smaller than a typical rate for a large capacity well, the capture results are independent of the applied rate because the capture fraction is normalized by the hypothetical pumping rate. The capture results are insensitive to the applied rate if the model is more or less linear. Non-linearities occur when simulating groundwater evapotranspiration (ET) or unconfined conditions. The TVS groundwater model is relatively linear because it does not simulate groundwater ET and the simulated groundwater level changes within the unconfined aquifer are relatively small. ET is not simulated within the MODFLOW model because all ET is thought to occur within the vadose zone which is not simulated by MODFLOW. The GSFRM model simulates ET from the vadose zone.

The hydraulic conductivity of the lowermost layers (3 and 4) are on the order of 10^{-3} m/day (3 x 10^{-3} ft/day) which made it difficult to obtain the desired pumping rate of 100 m^3/day. There were approximately 1,000 cells for which the pumping rate had to be reduced to as little as 10^{-1} m^3/day (4 ft^3/day).

All model simulations were done using the OASIS high-performance computing cluster housed at the DRI. A single model run required approximately 50 seconds using a single core. The total time required to run 26,936 groundwater model simulations would be approximately 16 days if only one computer were used. Using 24 cores, the total time for all model runs was reduced to 16 hours.

Pre-analysis showed that global mass-balance error strongly affects capture calculations. This study used a Newton-Raphson formulation to obtain the solution of the unconfined groundwater-flow problem. The maximum head change tolerance between iterations was set as default of 10^{-3} m (3 x 10^{-3} ft). A smaller head change tolerance than this often leads to smaller mass-balance error and more realizable capture calculation results. However, this results in longer model run times. To address this issue, the study used a dynamic head change tolerance to reduce model run time but still guaranteed reliable capture calculations. The mass-balance error was checked at the end of every model run given the initial head change tolerance of 10^{-3} m (3 x 10^{-3} ft). If the mass-balance error was larger than 1 m^3/day (35 ft^3/day), the head change tolerance was reduced until the mass-balance error threshold was satisfied. The mean and standard deviation of absolute mass-balance errors for 26,936 model runs are 0.35 and 0.29 m^3/day (12 and 10 ft^3/day), respectively. These errors are small in comparison with the well withdrawal rate of 100 m^3/day (3,531 ft^3/day). The mass-balance error has insignificant impact on the capture calculations.

Figure 11 shows the maps of water capture from Lake Tahoe and from all the streams in the model domain (i.e. beyond just the TVS groundwater basin) given the pumping locations in different layers. Note that dry cells within the uppermost model layer (layer 1) were excluded from the capture analysis and are shown without color. Dry cells result when the predicted water table drops below the bottom cell elevation. This can occur in areas of low hydraulic conductivity and topographic highs as the layer elevation is relative to surface elevation.

As steady-state models were used, the total water withdrawal from the aquifer always equals the summation of the water captured from rivers and the water captured from Lake Tahoe. The 0.5 capture fraction contour, where half of the water comes from the depletion of the streams and half comes from depletion of the Lake Tahoe, is near the Lake Tahoe Airport. North of the Lake Tahoe Airport, most of pumped water is a result of depletions from Lake Tahoe and south of the Lake Tahoe Airport, most of pumped water is from stream depletion.

Capture maps constructed for four model layers are relatively similar as shown in Figure 11. This is a result of fairly good hydraulic connection vertically. For example, the absolute differences in capture fractions by pumping in layer 1 versus pumping in layer 2 are less than 0.05.

Pumping in deeper layers resulted in more water withdrawal from Lake Tahoe than streams. For example, the contour of 0.1 capture fraction retreats southward of the Lake Tahoe when moving the pumping locations from layer 1 to layer 4.

The capture maps can be used to manage the TVS basin in a manner that minimizes impacts to surface water bodies. Given that the size of Lake Tahoe depletions from groundwater pumping are not going to impact lake levels, future management of the aquifer system can focus on minimizing stream depletion.

The capture maps shown in Figure 11 suggest that the impacts of groundwater pumping on streamflow will be limited to the area south of the South Lake Tahoe airport. A pumping management area is proposed that encompasses the region in which stream capture is greater than 50 percent in any model layer (see Figure 11). The resulting area is shown in Figure 12.

Specific guidelines regarding the depletion of interconnected surface water were recently developed in an Analysis of Basin Conditions (ABC) for the TVS Basin (Pohll *et al.*, 2016). The ABC was prepared in response to the Sustainable Groundwater Management Act (SGMA) that was signed into law in September 2014 by Governor Jerry Brown to ensure that California's most at-risk groundwater basins are managed sustainably. The ABC is an alternative to a groundwater sustainability plan (GSP) for basins that have operated within its sustainable yield for at least a 10-year period. The ABC outlined pumping thresholds that would ensure that no undesirable results would occur to streams. Specifically, the minimum threshold is defined as baseflow depletions in excess of 12,400 AFY—equivalent to 10 percent of the average annual runoff.

To ensure that this threshold is not exceeded, we are recommending that pumping rates do not exceed 12,400 AFY within the pumping management area. Limiting the total pumping to the region with streamflow depletions greater than 50 percent will ensure that stream ecology is not harmed.

It is important to note that a majority of the pumping wells and well discharge are located north of the proposed management area. North of the pumping management zone stream depletions are much smaller so groundwater pumping does not significantly impact streamflow. There are only four active large capacity wells within the proposed management area (Figure 12). These wells include Elks Club #2, Bakersfield, Arrowhead #3, and South Upper Truckee #3. For reference, these wells pumped a total of 1,200 AFY in water year 2016. Although pumping was reduced due to state drought water restrictions, current pumping in the proposed management area is well below the threshold value of 12,400 AFY.

The California-Nevada Interstate Compact Concerning Water of Lake Tahoe, Truckee River, Carson River, and Walker River Basins (Compact) approved in 1971 allocates a maximum of 12,493 AFY for use in the South Lake Tahoe area (California SWRCB, 1979) and of this amount the District has a right to a total maximum allocation of 9,528 AFY.

With these legal restrictions in place and the fact that 80 percent of groundwater pumping is currently located north of the proposed management area, it is highly unlikely that pumping will exceed the 12,400 AFY threshold.

5.0 BMO #5, ACTION 3 CLIMATE CHANGE EFFECTS

5.1 IMPACTS TO GROUNDWATER RECHARGE

The global climate projections from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model dataset referenced in the Intergovernmental Panel on Climate Change Fifth Assessment Report were used to derive the expected climate change in the TVS Basin. The CMIP5 runs are archived at multiple web locations, and for this study the climate change data was accessed through the USGS at https://www2.usgs.gov/climate_landuse/clu_rd/nccv.asp.

There are four representative concentration pathways (RCPs) that were selected as part of the CMIP5 global climate projection runs. They are defined to reflect total radiative forcing, which is a cumulative measure of human emissions of greenhouse gases from all sources expressed in watts per square meter (W/m^2) by the year 2100. Figure 13 shows the different RCPs used in CMIP5. For this study we focus on RCP 8.5 and RCP 4.5.

For the two selected RCPs the climate change projections for Lake Tahoe max air temperature, min air temperature, and precipitation are presented in Figure 14, 15 and 16 respectively. The max air temperatures are projected to increase between 5-10°F and the min air temperature are projected to increase between 4-9°F by the end of the 21st century. The precipitation projections however do not show a clear trend, with some years showing above normal precipitation and other years showing a drought (Figure 16).

Since there is no general agreement among GCMs in terms of simulated precipitation, selected projections focused on a subset of GCMs as identified by Lynn *et al.*, (2015) which are representative for use in California Water Resources applications. Table 2 provides a summary of the different RCPs used to evaluate precipitation and temperature change in South Tahoe for the future period compared to the baseline period. As noted in Table 2, the future simulation period represents end of the century conditions (2075-2099). In other words, the temperatures are adjusted instantaneously thereby representing worst-case climate conditions for this century.

The GCM models identified by Lynn *et al.*, 2015 were then grouped into various categories based on the relative precipitation and temperature magnitudes. Figure 17 shows the percent change of the future period compared to the baseline for both temperature and precipitation. The models were grouped to create five climate scenarios named Q1 to Q5. The climate scenarios represent a range of likely outcomes,
Q1 – Drier with less warming; Q2 – Drier with more warming; Q3 – Wetter with more warming;
Q4 – Wetter with less warming; and Q5 – Warming only with no change in future precipitation.

A drought scenario (Q6) was created by piecing together 2012-2015 and 1987-1994 droughts to create a 12 year drought scenario. The baseline and drought scenario precipitation record are shown in Figure 18. A 5°F temperature increase was added to the drought scenario (Q6) to represent average mid-century (2060) temperature increases based on 30 climate models representing high emission scenarios.

A baseline scenario is also simulated which represents historical conditions over the last 33 years (1983 – 2015). No changes to the measured precipitation and temperature records were done to the baseline scenario.

The seven climate scenarios (six future scenarios and one baseline historical) were then applied to the GSFRM to calculate changes in groundwater recharge. Figure 19 shows the average groundwater recharge from the resulting scenario simulations. Over the baseline period (1983 – 2015) groundwater recharge averaged 39,000 AFY.

The two wetter climate scenarios showed increased groundwater recharge. The Q3 climate scenario, which represents a 28 percent increase in precipitation and a 9.3°F increase in temperature, resulted in a 24 percent (47,000 AFY) increase in groundwater recharge. With less intense warming the Q4 scenario, which also represents a 28 percent increase in precipitation but with only a 5.3°F temperature increase, resulted in a 34 percent increase in recharge or 51,000 AFY.

Scenario Q5 represents baseline precipitation (i.e. no change) with a 7.3°F increase in temperature. Again, the increased temperature leads to increased ET and runoff which resulted in 5 percent less groundwater recharge (36,0000 AFY).

Increased temperatures (scenarios Q1 and Q2) result in increased ET and runoff which translates into less groundwater recharge. Scenario Q1, which represents 17 percent less precipitation with 5.3°F warming, resulted in 24 percent (29,000 AFY) less recharge. With additional warming scenario Q2 (9.3°F increased temperatures and 17 percent less precipitation) resulted in 32 percent less recharge (26,000 AFY). The drought scenario (Q6) had similar results to Q2 with 32 percent less recharge (26,000 AFY).

5.2 GROUNDWATER STORAGE AND WATER LEVEL IMPACTS

The climate scenarios were used within the TVS groundwater model to assess changes in groundwater storage throughout the TVS Basin. The initial condition for the groundwater model is the result of the steady-state model with no pumping. Thereafter, water levels respond to groundwater recharge associated with each climate scenario and pumping from 16 active large capacity wells. The pumping rates were averaged over the 2009 – 2016 period to represent future conditions and are the same rates used in the capture zone analysis (Table 1). The simulations are run for 33 years to represent the later century climate period. The only exception is the drought scenario which only simulates 12 years which is the maximum expected continuous drought period.

The results are presented in two ways. First, cumulative groundwater storage changes over the TVS Basin are presented over the simulation period. The sign convention for the storage change calculations is such that negative represents falling water levels and positive represents increasing water levels. Second, the difference in water levels between the baseline simulation and a specific scenario are mapped to show where water levels might change within the basin under a changing climate. The sign convention for the water level changes is such that negative denotes rising water levels and positive denotes falling water levels relative to baseline conditions. The water level difference graphics are provided at the end of the respective simulation (either 12 or 33 years).

Simulated change in groundwater storage within the TVS Basin for the six climate scenarios and the baseline is shown in Figure 20. All scenarios show declining water levels and groundwater storage during the first few years as the basin develops a new equilibrium position due to pumping. The baseline simulation, which does not have any changes in temperature and precipitation nearly reaches a new equilibrium position after approximately 10,000 acre-feet is removed from storage.

Scenario Q4, which represents wetter and warmer conditions, shows groundwater storage and water levels that are slightly above pre-development conditions. The increased precipitation (28 percent) offsets increases in evapotranspiration due to warming (5.3°F) and pumping above predevelopment conditions. Groundwater storage varies with annual variations in climate, but after the first decade, cumulative storage changes are slightly positive (3,000 acre-feet) which indicates that on average water levels are just above pre-development conditions. Water level changes at the end of the 33 year simulation between the baseline are shown in Figure 21. Most of the region experiences water level increases between 0 – 10 feet. There is a small area in the southeast portion of the TVS Basin near Saxon Creek where water levels increase more than 10 feet.

Scenario Q3, which represents wetter (28 percent) and significantly warmer (9.3°F) conditions, has groundwater storage and water levels that are near pre-development conditions. In this case the increased temperatures cause more evapotranspiration which counteracts the increased precipitation. After the first decade, cumulative storage changes are near zero which indicates that on average water levels are at pre-development conditions. Figure 22 shows the water level changes at the end of the 33 year simulation between the baseline. Most of the region experiences water level increases between 0 – 10 feet. There is a small area in the southeast portion of the TVS Basin near Saxon Creek where water levels increase more than 10 feet.

Scenario Q5, which represents increases in temperature (7.3°F) but no change in precipitation, shows groundwater storage slightly below pre-development conditions. After the first decade groundwater storage is typically 1,000 – 3,000 AF less than pre-development conditions. Figure 23 shows the water level changes at the end of the 33 year simulation between the baseline. Most of the region experiences water level declines between 0 – 10 feet with largest declines in the center portion of the TVS Basin. Neutral water level changes occur at the north end of the TVS Basin, along the south shore of Lake Tahoe, at the southeast portion of the TVS Basin near Saxon Creek, and at the extreme south end of the TVS Basin, near the point of entry of the South Upper Truckee River into the TVS Basin.

Scenario Q1, which represents dryer (-17 percent) and warmer (5.3°F) conditions, causes more severe changes in groundwater recharge and water levels. After the first decade groundwater storage is typically 10,000 AF less than pre-development conditions. Figure 24 shows the water level changes at the end of the 33 year simulation between the baseline. Most of the region experiences water level declines between 0 – 10 feet with only small areas with water level declines slightly larger than 10 feet.

A similar result is found for Scenario Q2, which represents dryer (-17 percent) and hotter (9.3°F) conditions. The additional temperature increases reduce recharge and lead to storage values that are 14,000 AF less than pre-development conditions. Figure 25 shows the water level changes at the end of the 33 year simulation between the baseline. Most of the region experiences water level declines between 0 – 10 feet. Groundwater level declines in excess of 10 feet are also indicated along the northwest and east margins of the Twin Peaks area, and along the east central margin of the TVS Basin near Heavenly Valley Creek.

Scenario Q6, which represents the severe drought condition, leads to the most rapid water level declines due to significantly less precipitation (-24 percent) and moderate temperature increases (5.3°F). The drought scenario leads to average groundwater storage that is 10,000 AF less than pre-development conditions for the final two years of simulation. Figure 26 shows the water level changes at the end of the 12 year drought simulation between the baseline. Most of the region experiences water level declines between 0 – 10 feet. Groundwater level declines in excess of 10 feet are also indicated along the northwest margin of the Twin Peaks area, and in the southeast along Saxon Creek

5.3 RESPONSE TO EXTERNAL REVIEW OF CLIMATE CHANGE ANALYSIS AT TAHOE VALLEY SOUTH

Very recently, Christian-Smith, 2017 developed a white paper to provide water managers an overview of climate models, a framework to evaluate various approaches of incorporating climate change data into state-level water planning documents, and recommendations on how to incorporate future climate projections into local Groundwater Sustainability Plans. As noted above, an ABC analysis was conducted for the TVS Basin (Pohll *et al.*, 2016) as an alternative to a Groundwater Sustainability Plan. The ABC analysis broadly discussed potential impacts of climate change on the TVS Basin. The Christian-Smith, 2017 whitepaper provided an evaluation of climate change approaches for ten alternative sustainability plans that incorporated climate change analysis of which the TVS Basin was included.

Their assessment included a brief statement of how climate change data were used in the alternative plan. The Christian-Smith, 2017 whitepaper indicated that *Temperature and precipitation were projected using the Bay Delta Conservation Plan climate model, which downscales multiple GCMs to 12 km^2 grid cell resolution using the emission scenarios A1, B, B1, and A2 from the IPCC AR4. Projections for the South Tahoe area were run from 2010 to 2100.* Although these data were used in a detailed climate change analysis (Huntington and Niswonger, 2012) for nearby watersheds (Incline Creek, Third Creek, and Galena Creek which are at the north end of the Lake Tahoe Basin), this analysis was only used to provide an example of the potential changes that could occur in a snow-dominated watershed and it did not apply directly to the TVS Basin.

Christian-Smith, 2017 correctly identified priority management objectives that were developed in the alternative ABC report in response to climate change. Within the Analysis of Undesirable Results (Section 5.0) a 13 year drought period was generated to determine the impact of a 20 percent decrease in precipitation on groundwater recharge and associated reductions in groundwater storage. To ensure that groundwater supplies are maintained at sustainable levels into the future, groundwater storage changes will be monitored on an annual basis. A minimum threshold in cumulative groundwater storage change was developed to ensure that existing water supply wells within the TVS Basin could meet the Maximum Daily Demand.

The Christian-Smith, 2017 whitepaper developed two findings for the TVS Basin:

- *Aside from providing recharge estimates, it is not clear how the projections are being incorporated into specific planning and management activities.*
- *All GCM models used projected that rising snow-level elevations may reduce snowpack volumes and snowmelt throughout the Sierra Nevada Range. However, the models do not agree on the impact this will have on recharge, which suggests that an adaptive approach combined with further research in this area is warranted.*

The main problem with the Christian-Smith, 2017 assessment for the TVS Basin is that the ABC analysis is not the only document that describes how water managers are addressing climate change issues. In addition to the ABC report, the GWMP (Kennedy-Jenks, 2014) was submitted as a second Alternative Plan for SGMA regulations. The GWMP outlined a number of Basin Management Objectives (BMO) to address specific issues related to groundwater sustainability. One BMO (BMO #5, Action #3) is dedicated to determine the impacts of climate change on the TVS Basin and this report details the results.

The climate change analysis presented in this report suggests that the TVS Basin will remain in a sustainable condition for all of the climate scenarios investigated so no additional management activities are required at this time beyond ongoing monitoring. Therefore, their first finding that climate projections are not being incorporated into planning activities is not valid.

The second finding suggests that the GCM models do not agree on the impact this will have on recharge which is correct, but groundwater recharge (25,700 AFY) for the worst-case scenario (Dry/Hot-Q2) exceeds the groundwater allocations defined (12,500 AFY) for the TVS Basin in the California-Nevada Interstate Compact as well as historical (1983 – 2015) groundwater extractions (7,700 AFY), and the maximum allocation for the District (9,500 AFY). Beyond ongoing monitoring, additional research on the impacts of climate change on the groundwater resources in the TVS Basin is not needed until CO_2 emissions far exceed those being predicted in RCP 8.5 (worst case).

6.0 BMO #7, ACTION 4 MONITORING NETWORK

Implementing the Monitoring Program, the District collects data on a regular basis to assess groundwater conditions within the TVS Basin. Groundwater level measurements are collected by the District at designated groundwater supply and monitoring wells as designated by the 2014 Groundwater Management Plan (GWMP) using identified protocols and other supporting documents. Samples for groundwater quality are collected by the District at all public water system wells in accordance with the requirements of the California Department of Drinking Water (DDW). Additional groundwater level and quality data are compiled from other agencies that collect data in the TVS Basin. The District coordinates the collection of groundwater pumping volumes in the TVS Basin by the District and other water systems.

The District collects groundwater levels semiannually from a suite of 30 representative wells in order to facilitate analysis of seasonal and long-term trends in groundwater elevation. Semi-annual measurements are collected in May and November of each year in all 30 observation wells; additionally, 13 of the observation wells are equipped with data loggers that measure and record groundwater head elevation twice daily. The locations of these monitoring wells are shown in Figure 27.

To ensure that water quality of drinking water is maintained, the Water Code includes a requirement that water purveyors regularly monitor groundwater quality at each drinking water source (i.e., well). The suite of required constituents includes various inorganic chemicals, radioactivity, and organic chemicals. This section describes the monitoring performed by STPUD and by other entities extracting water from the TVS Basin. STPUD collects samples of groundwater from 15 active production and monitoring wells on at least an annual basis (from June to August), and submits those samples for analysis of the full suite of Title 22 analytes.

The District reviews the collected data with respect to historical data for each sampling location to assess changes in trends. Groundwater quality data is compared to drinking water quality standards as defined by the California Department of Drinking Water (DDW), and the water quality objectives for groundwater in the TVS Basin provided in the Lahontan Regional Water Quality Control Board (LRWQCB) Basin Plan. The Basin Monitoring Program is modified by adding/removing wells over time based on the ongoing assessment of basin conditions; modifications are addressed in Annual Reports.

BMO #7, Action 4 was identified so the District could reevaluate its groundwater monitoring well network to improve the ability to track changes in groundwater levels and quality in the TVS Basin. The analysis focused on the following items in preparing recommendations for additional monitoring locations:

- The spatial distribution of water supply wells to ensure that there are sufficient monitoring wells to observe the potential for localized drawdown.
- The spatial distribution of groundwater contamination zones. The primary contaminant of concern is the PCE plume which originates near the "South Y" area and extends to the north (Figure 28).
- The simulated changes in groundwater levels associated with climate change. The worst-case scenario Q2 (Hotter/Dryer) was used to determine locations where water levels may decline the most.

Figure 27 shows the current monitoring well network for water levels in addition to the location of active water supply wells and predicted water level declines for the Q2 climate change simulation. There are five wells (Henderson Test Well, South Upper Truckee 1-3, and EX1) where groundwater levels are monitored semi-annually in the Christmas Valley region where one would expect the most rapid declines under hot and dry conditions. All five of these wells will provide useful data to determine if long-term declines in water levels may be due to climate change. Most importantly, EX1 and the Henderson Test Well are located a good distance from water supply wells and should be easier to interpret climate only signals.

It may also be helpful to add additional monitoring wells in the southeast of the TVS Basin along Saxon Creek. This is an area that may experience more significant water levels declines under dryer and hotter conditions. If new monitoring wells are drilled in this location, they should be kept away from the stream a minimum distance of ¼ mile to ensure that they are measuring regional groundwater conditions and not localized effects from the stream.

In the remainder of the TVS Basin, the monitoring well network generally captures localized drawdown effects near water supply wells and regional responses. The one exception to this is the region north of the "South Y" area where there are four water supply wells not under the control of the district. These include the Tahoe Keys wells 1, 2, and 3, and the Lukins Brother's well #1. Additional monitoring wells should be collocated with the water supply wells to monitor localized drawdown. At a minimum, the water supply wells could be included in the semi-annual network if the wells could be turned off for a minimum of 12 hours. New monitoring wells could be drilled near each of these wells at approximately the same depth as the water supply wells.

In addition to monitoring water levels, regular water quality monitoring is needed to ensure that contaminant plumes do not encroach on water supply wells. In particular, there is a PCE plume located north of the "South Y" area as shown in Figure 28. Beyond the annual water quality sampling at the water supply wells a PCE monitoring plan should be developed in conjunction with the ongoing feasibility study of remedial alternatives to mitigate the regional South "Y" Plume. The monitoring plan should include quarterly to bi-annual sampling to monitor the PCE plume extent, migration pathways, up-gradient source behavior, and to act as an early warning system for down-gradient receptor wells. Multi-depth sampling wells would be needed to identify plume depths and migration behavior.

7.0 CONCLUSIONS

The following conclusions can be drawn from this analysis:

- BMO #7, Action 3 - Sophisticated numerical modeling tools have been developed to assess the hydrologic conditions within the TVS Basin. The modeling framework improves water balance estimates of precipitation, streamflow, evapotranspiration, mountain-front recharge, infiltration, and groundwater flow. The models provide a quantitative tool for evaluating future conditions as well as furthering the overall hydrogeological understanding of groundwater conditions in the TVS Basin.

- BMO #4, Action #2 - Most of the recharge occurs in the Crystal Range of the Sierra Nevada and Carson Range. Annual recharge ranges from 9 inches in the valley to upwards of 34 inches in the higher elevations. Groundwater recharge is largely dependent on annual precipitation and a regression equation was developed between annual precipitation at Hagan's Meadows climate station to groundwater recharge. Average annual recharge over the entire simulation period (1983– 2015) is 39,000 AFY. Steady-state and time-dependent (2, 5, 10, and 20 years) capture zones were created for the 15 active water supply wells.
- BMO #5, Action 1 - A baseflow depletion analysis was performed for local streams and Lake Tahoe separately over the simulation period 1983 – 2015. As pumping increased in the 1980s, baseflow depletion rates for Lake Tahoe steadily increased from just under a 1,000 AFY in 1983 to an average of 5,900 AFY from 2000 – 2015. The depletion rates for streams steadily increased from a few hundred AFY in 1983 to an average of 2,500 AFY from 2000 – 2015. Following 2000, the baseflow reduction from streams represents 2 percent of the average annual runoff (124,000 AFY). Capture maps from Lake Tahoe and streams were created. Results revealed two areas where the sources of water withdrawal are different. North of the Lake Tahoe Airport, most of water withdrawal is from Lake Tahoe. South of the South Lake Tahoe Airport, most of water withdrawal is from streams. To ensure that this threshold is not exceeded, we are recommending that pumping rates do not exceed 12,400 AFY south of the airport to ensure that stream ecology is not harmed.
- It is important to note that a majority of the pumping wells and well discharge are located north of the proposed management area. North of the pumping management zone stream depletions are much smaller so groundwater pumping does not significantly impact streamflow. There are only four active large capacity wells within the proposed management area (Figure 12). These wells include Elks Club #2, Bakersfield, Arrowhead #3, and South Upper Truckee #3. For reference, these wells pumped a total of 1,200 AFY in water year 2016. Although pumping was reduced due to state drought water restrictions, current pumping is the proposed management area is well below the threshold value of 12,400 AFY.
- BMO #5, Action 3 – Six climate scenarios were developed to assess the impact of a changing climate on the TVS Basin. They include drier with less warming (Q1), drier with more warming (Q2), wetter with more warming (Q3), wetter with less warming (Q4), warming only with no change in future precipitation (Q5), and a 12 year drought scenario (Q6). The two wetter scenarios resulted in groundwater recharge rates 24 and 34 percent larger than baseline conditions for the wet/hot (Q3) and wet/warm (Q4) scenarios, respectively. The dryer scenarios led to less recharge of 24 and 32 percent less than baseline, for the dry/hot (Q2) and dry/warm (Q1) scenarios, respectively. Increasing temperatures without changing precipitation (Q5) led to 5 percent less recharge as compared to baseline conditions. The drought scenario (Q6) resulted in 32 percent less recharge. The dry/hot scenario resulted in the largest water level declines with most regions experiencing declines of 0 – 10 feet on only small areas in the south and southeast with declines just over 10 feet. The TVS Basin will remain in a sustainable condition for all of the climate scenarios investigated so no additional management activities are required at this time beyond ongoing monitoring. Beyond ongoing monitoring, additional research on the impacts of climate

change on the groundwater resources in the TVS Basin is not needed until CO_2 emissions far exceed those being predicted in RCP 8.5 (worst case).

- BMO #7, Action 4 – Two areas were identified as needing additional groundwater monitoring:
    - The area just north of the South Y to monitor localized drawdown effects from wells not controlled by the District and to more thoroughly monitor the PCE contaminant plume in this region. The PCE monitoring plan should be developed in conjunction with the ongoing feasibility study of remedial alternatives to mitigate the regional South "Y" Plume.
    - Though less critical, additional monitoring in the southeast, near Saxon Creek, would help identify potential groundwater level changes due to climate change.

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Table 1. Pumping rates used in the future steady-state simulation.

Well	**Rate (AFY)**
Al Tahoe #2	365
Arrowhead #3	39
Bakersfield	849
Bayview	2,777
Elk's Club #2	144
Glenwood #5	393
Helen #2	201
Paloma	24
So. Upper Truckee #3	383
Sunset	510
Valhalla	377
TKWC #1	439
TKWC #2	112
TKWC #3	383
LBWC #1	176
LBWC #5	146
Total:	**7,318**

Table 2. GCMs with the time periods and RCPs used for this study

	Historical Period	**Future Period**	**RCPs for T**	**RCPs for P**
ACCESS-1.0	1981-2010	2075-2099	RCP 4.5, RCP 8.5	RCP 8.5
CanESM2	1981-2010	2075-2099	RCP 4.5, RCP 8.5	RCP 8.5
CCSM4	1981-2010	2075-2099	RCP 4.5, RCP 8.5	RCP 8.5
CESM1-BGC	1981-2010	2075-2099	RCP 4.5, RCP 8.5	RCP 8.5
CMCC-CMS	1981-2010	2075-2099	RCP 4.5, RCP 8.5	RCP 8.5
CNRM-CM5	1981-2010	2075-2099	RCP 4.5, RCP 8.5	RCP 8.5
GFDL-CM3	1981-2010	2075-2099	RCP 4.5, RCP 8.5	RCP 8.5
HadGEM2-CC	1981-2010	2075-2099	RCP 4.5, RCP 8.5	RCP 8.5
HadGEM2-ES	1981-2010	2075-2099	RCP 4.5, RCP 8.5	RCP 8.5
MIROC5	1981-2010	2075-2099	RCP 4.5, RCP 8.5	RCP 8.5

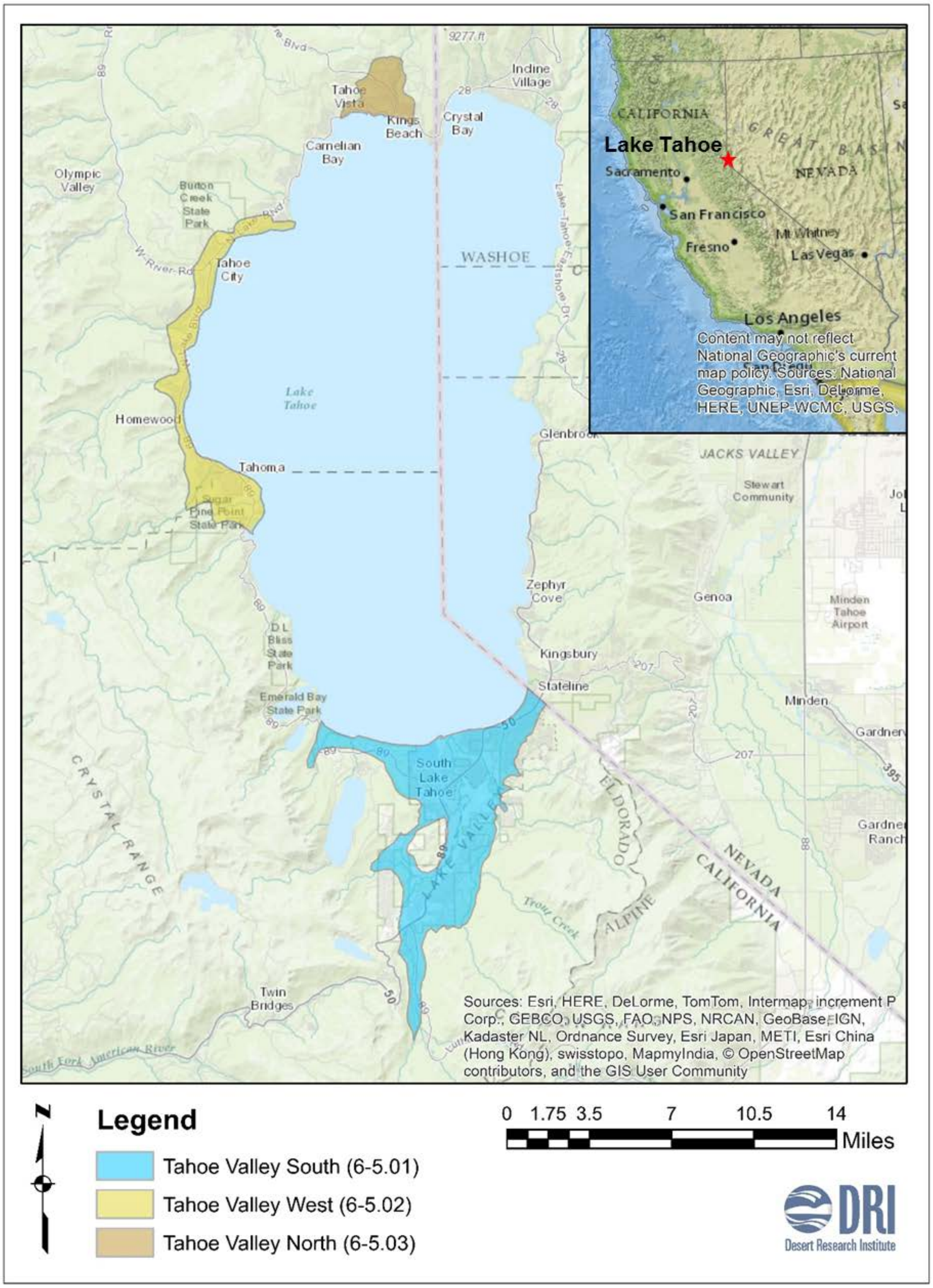


Figure 1. Lake Tahoe area regional map with California Department of Water Resources groundwater basins.

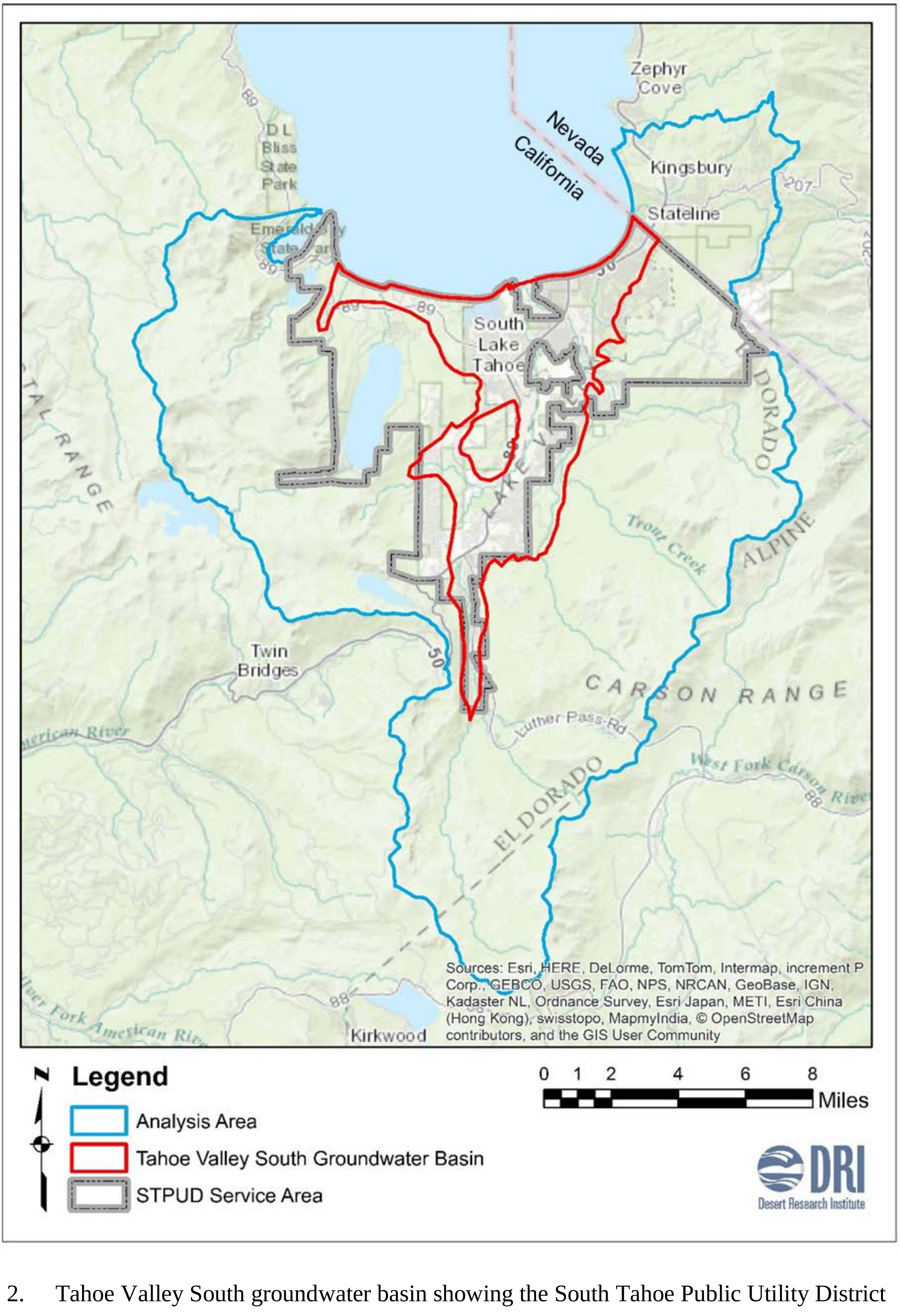
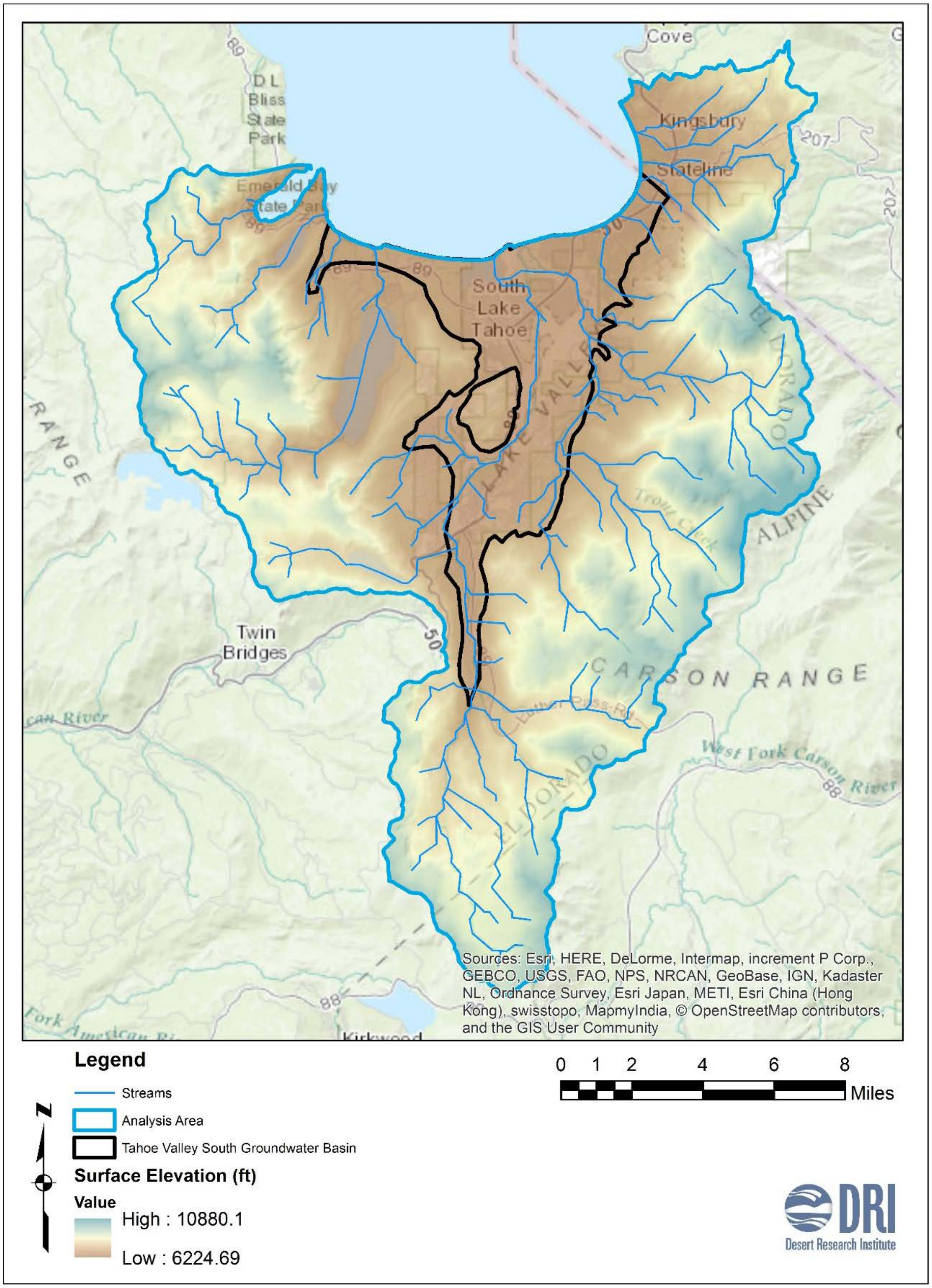
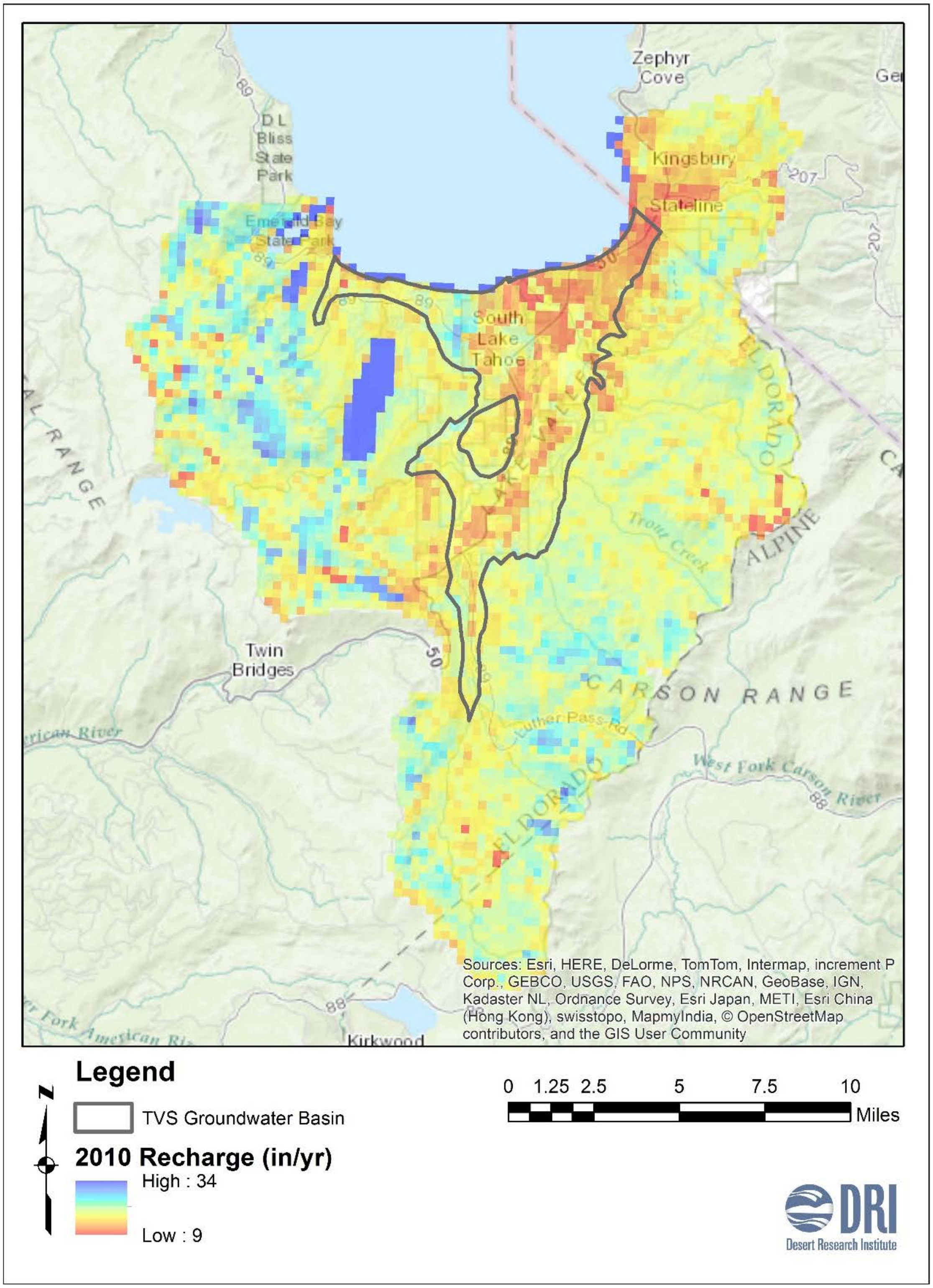


Figure 2. Tahoe Valley South groundwater basin showing the South Tahoe Public Utility District (District) service area and hydrologic analysis area.



Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 3. Topography and drainage network within the analysis area.



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 4. Groundwater recharge rates for 2010 as simulated with the GSFLOW model.

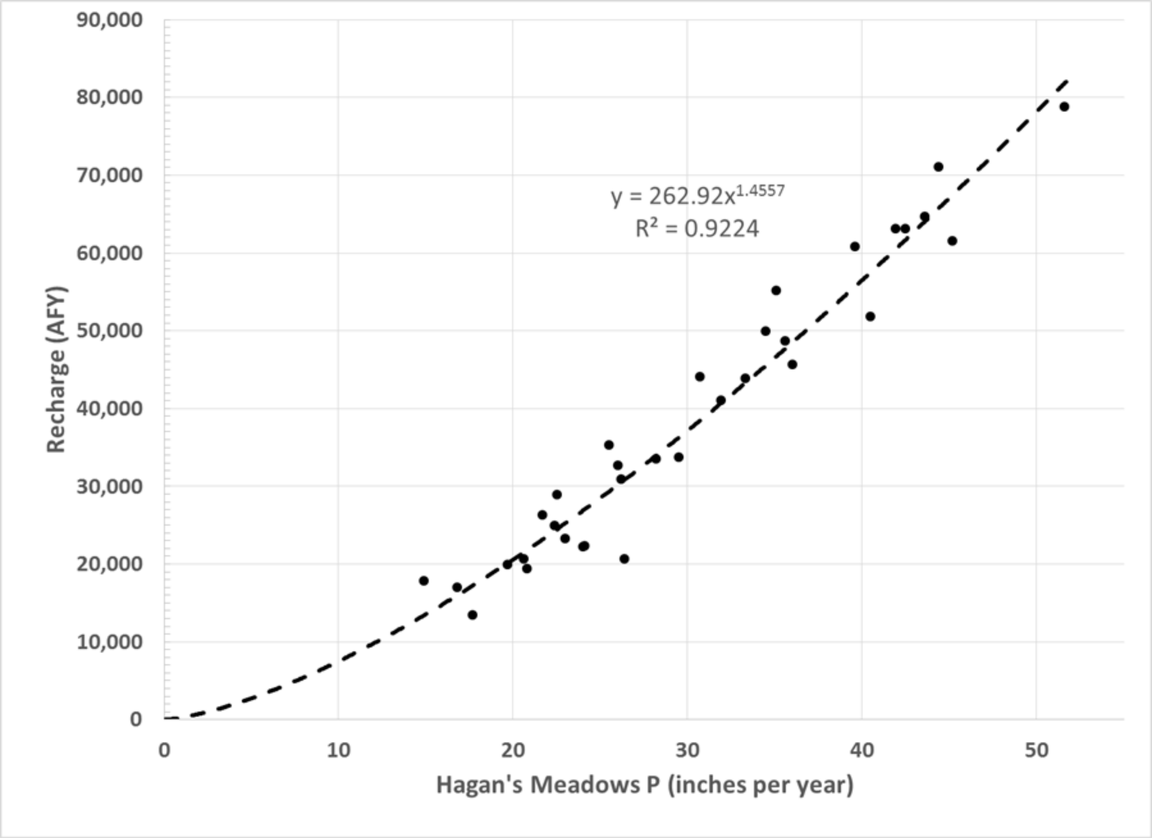


Figure 5. Hagan’s Meadow annual precipitation versus groundwater recharge within the hydrologic analysis area. Also shown is a non-linear regression.

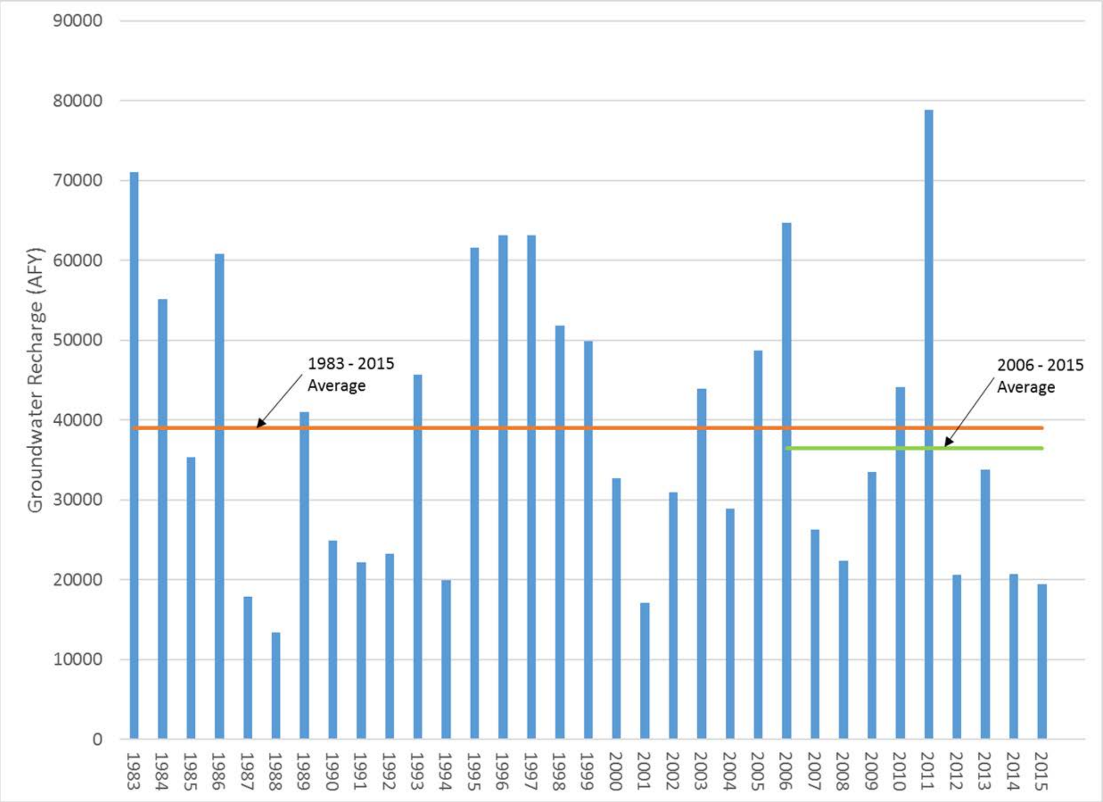


Figure 6. Groundwater recharge from water year 1983 – 2015. Green line represents average recharge over the period 2006 – 2015.

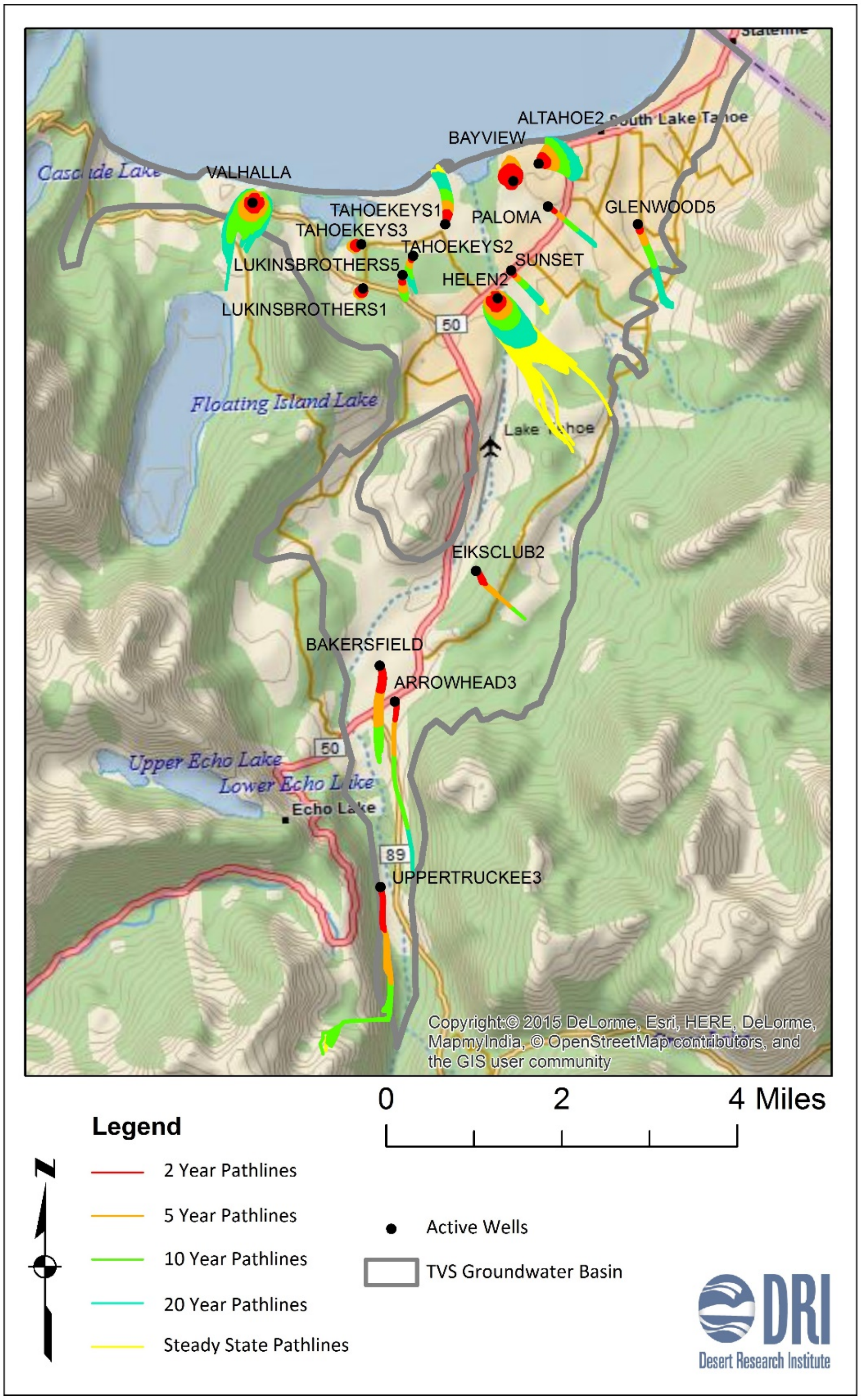


Figure 7. Steady-state and time-dependent capture zones for active wells within the TVS groundwater basin.

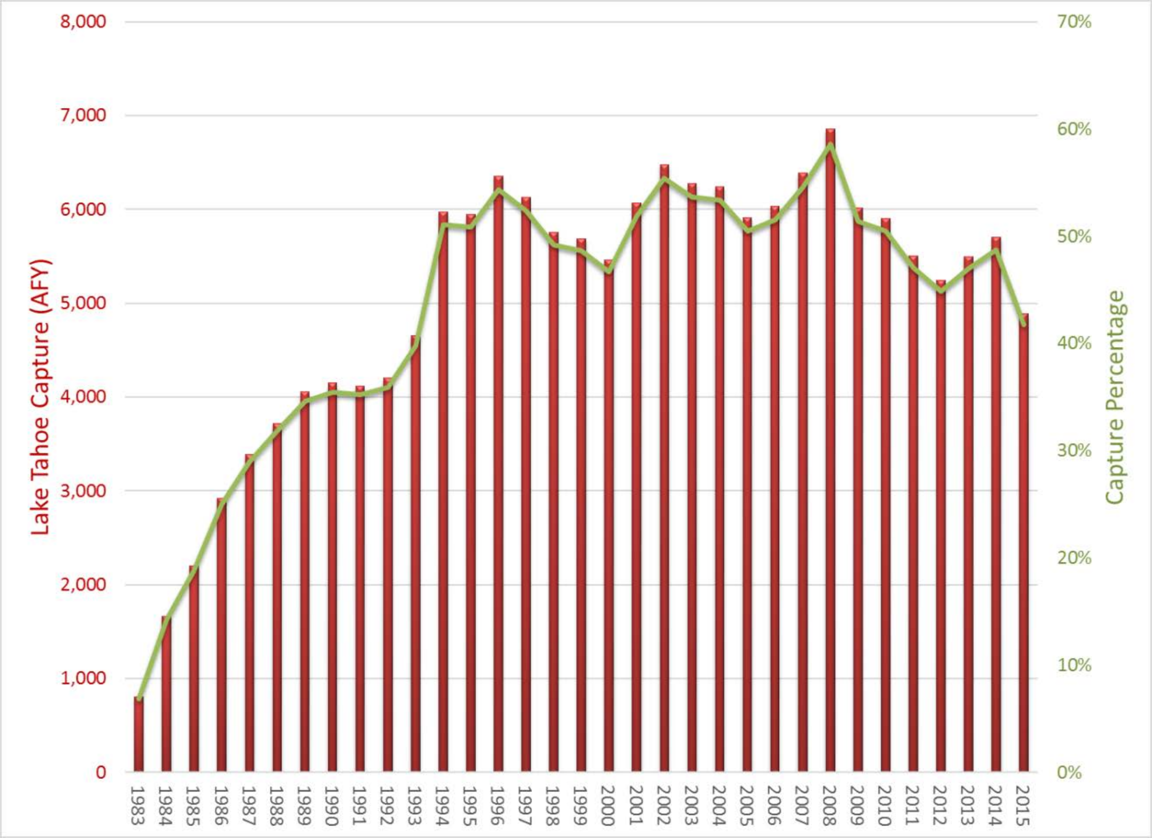


Figure 8. Baseflow depletion for Lake Tahoe caused by groundwater pumping. The capture percentage is calculated as the ratio of baseflow depletion and pre-pumping net groundwater flux to Lake Tahoe (11,700 acre-ft/yr).

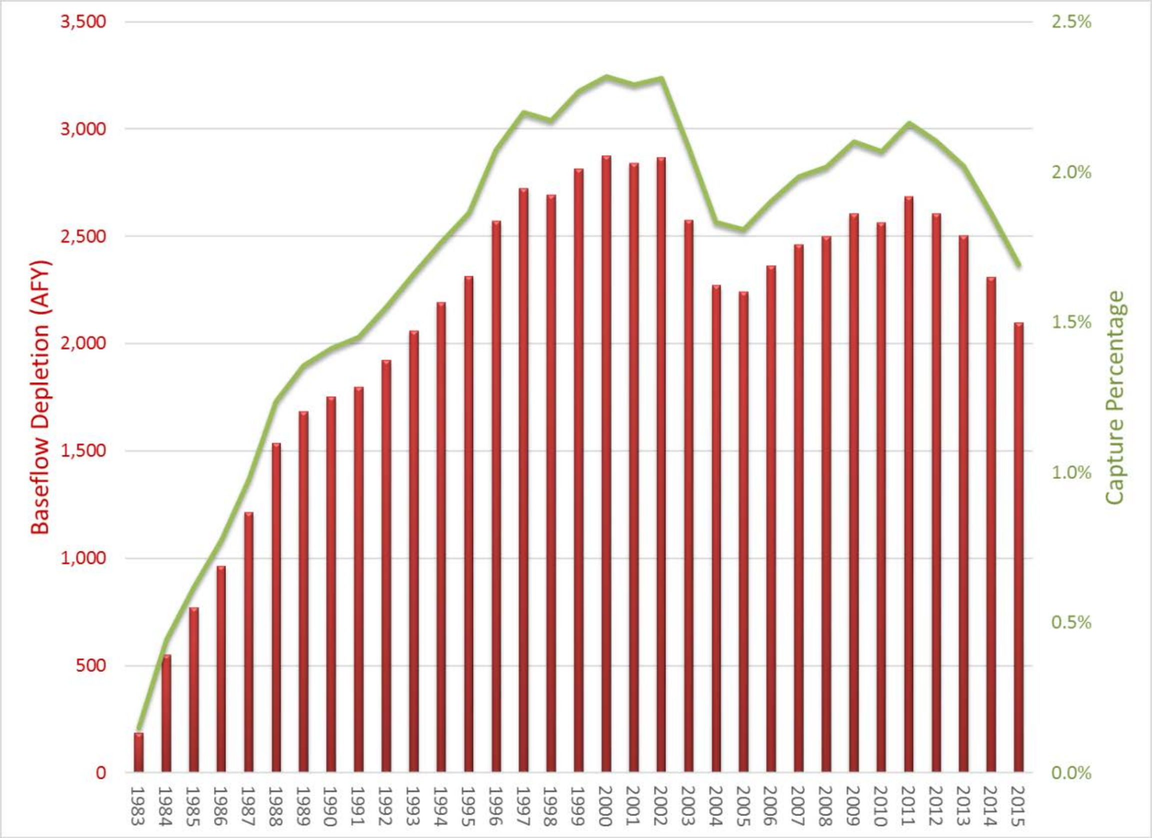


Figure 9. Baseflow depletion for the TVS Basin caused by groundwater pumping. The capture percentage is calculated as the ratio of baseflow depletion and average annual runoff (124,000 acre-ft/yr).

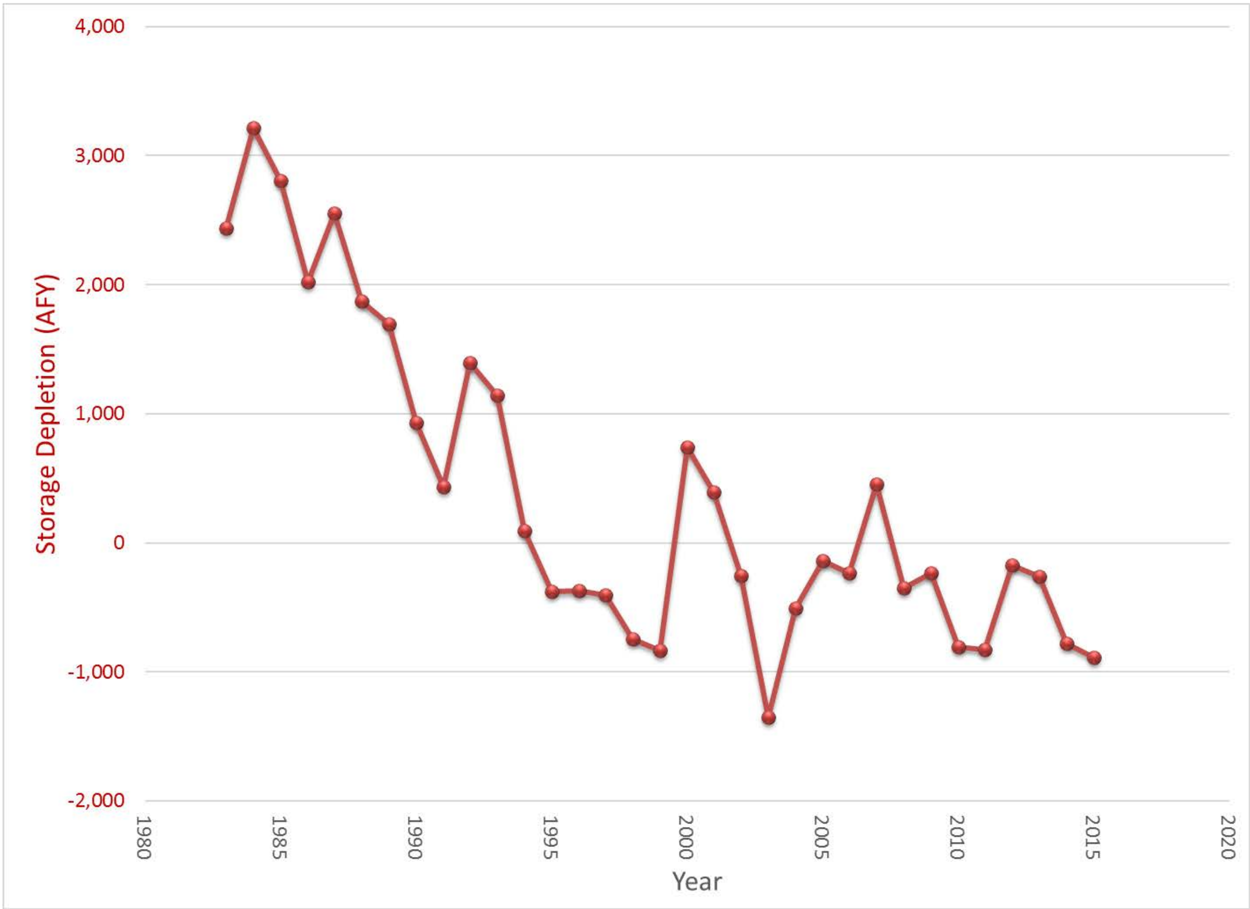
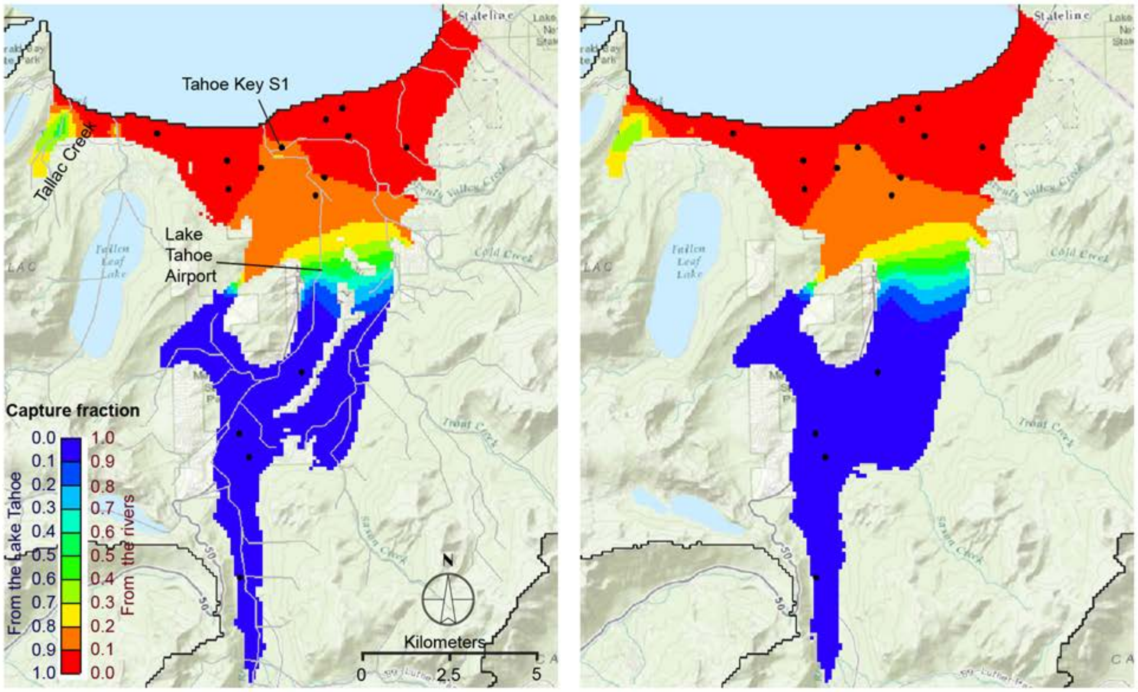
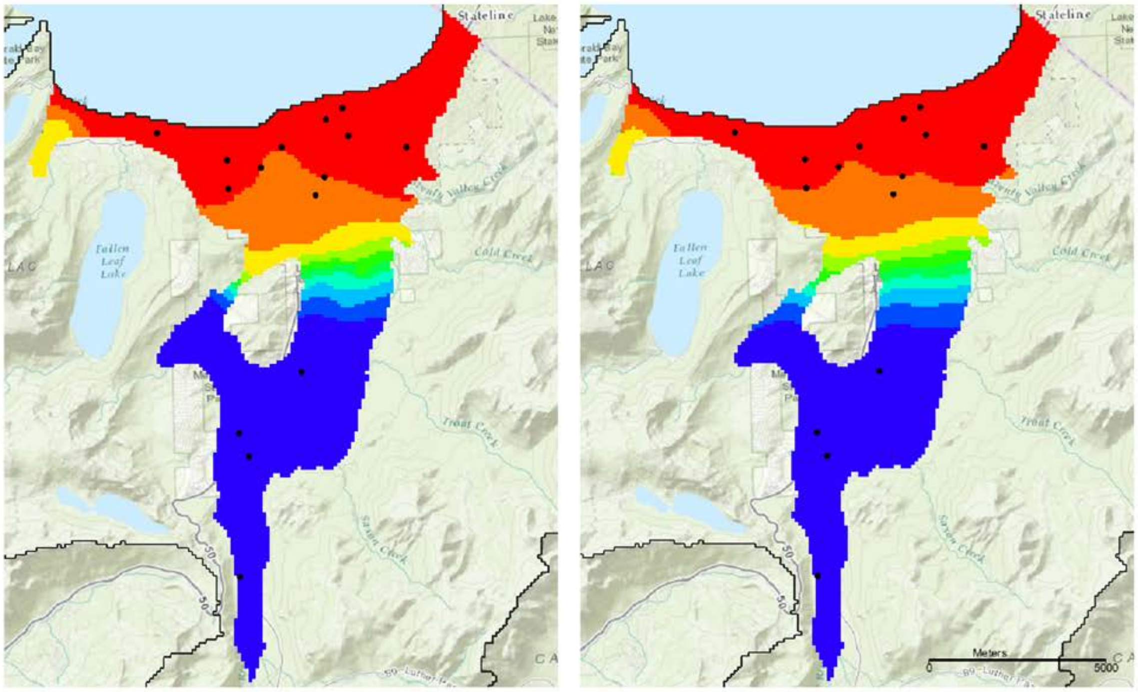


Figure 10. Storage depletion for the TVS Basin caused by groundwater pumping. Positive numbers indicate that there is more water coming out of storage for the pumping scenario.



(a) Layer 1 (b) Layer 2



(c) Layer 3 (d) Layer 4

Figure 11. Simulated capture fractions from Lake Tahoe and from all rivers in the model domain as a function of well locations in the TVS groundwater basin. For the surface layer (Layer 1); black dots are the location of the existing pumping wells and the grey lines indicate rivers and streams.

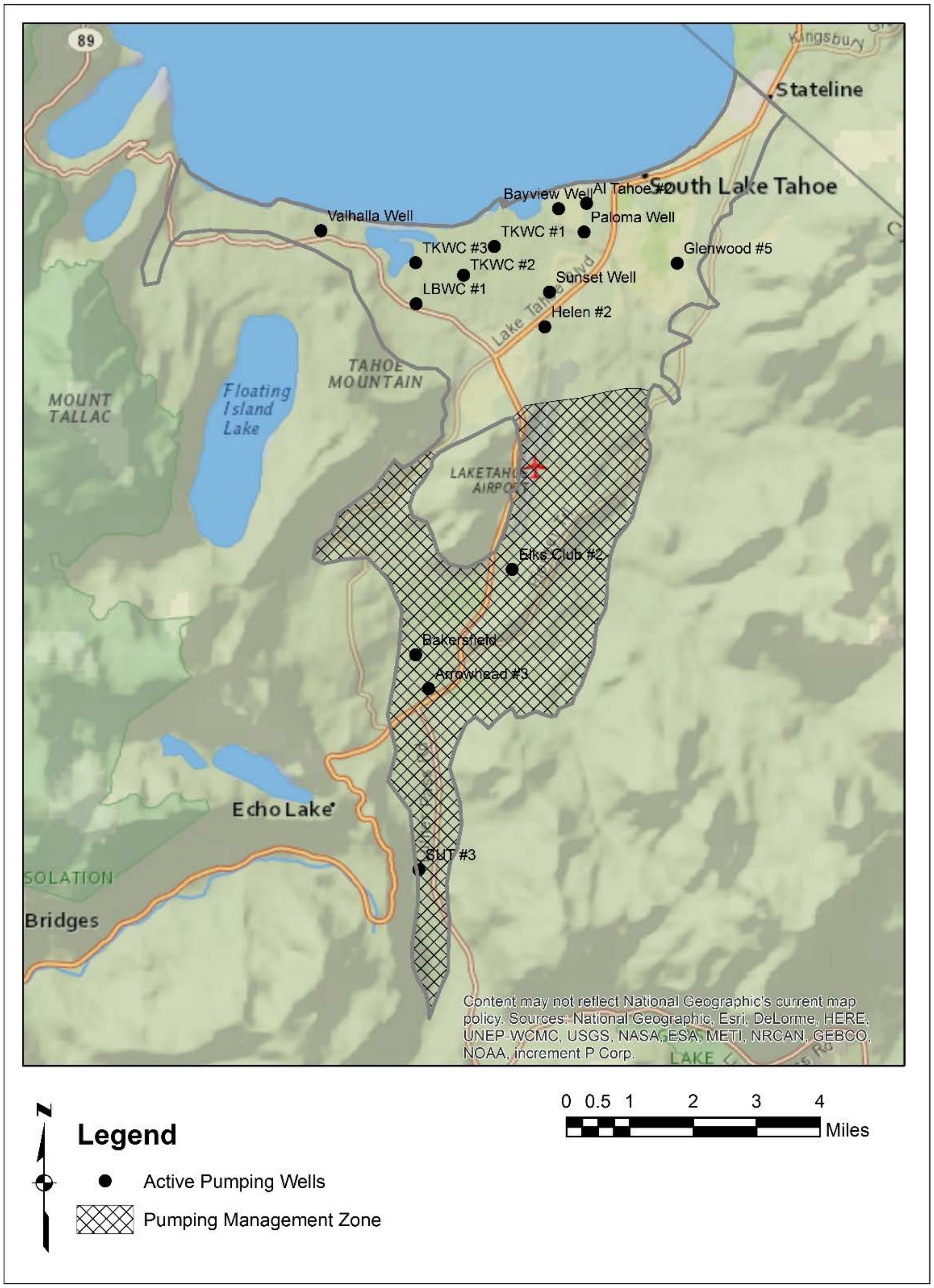


Figure 12. Proposed Pumping Management area which is based on simulated stream depletions in excess of 50 percent (see Figure 10).

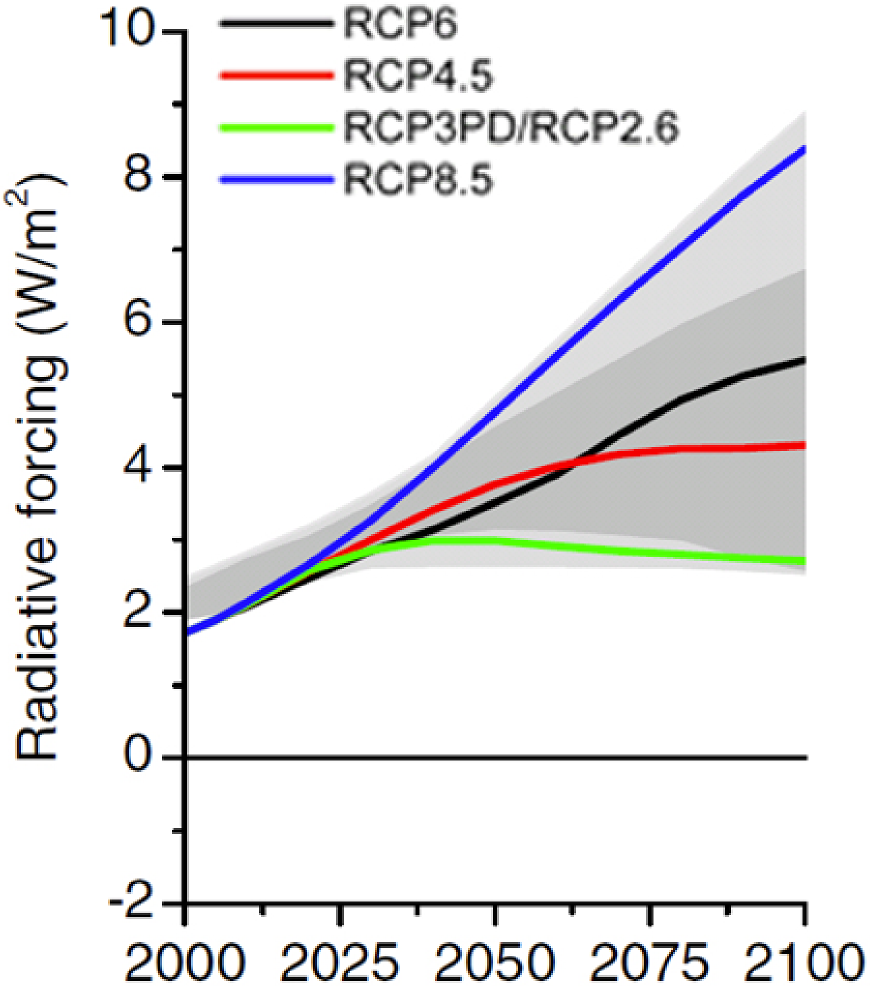


Figure 13. Representative concentration pathways (RCPs, expressed in watts per square meter) selected for the CMIP5 climate projections from van Vuuren *et al.* (2011). This study uses RCP8.5 and RCP4.5.

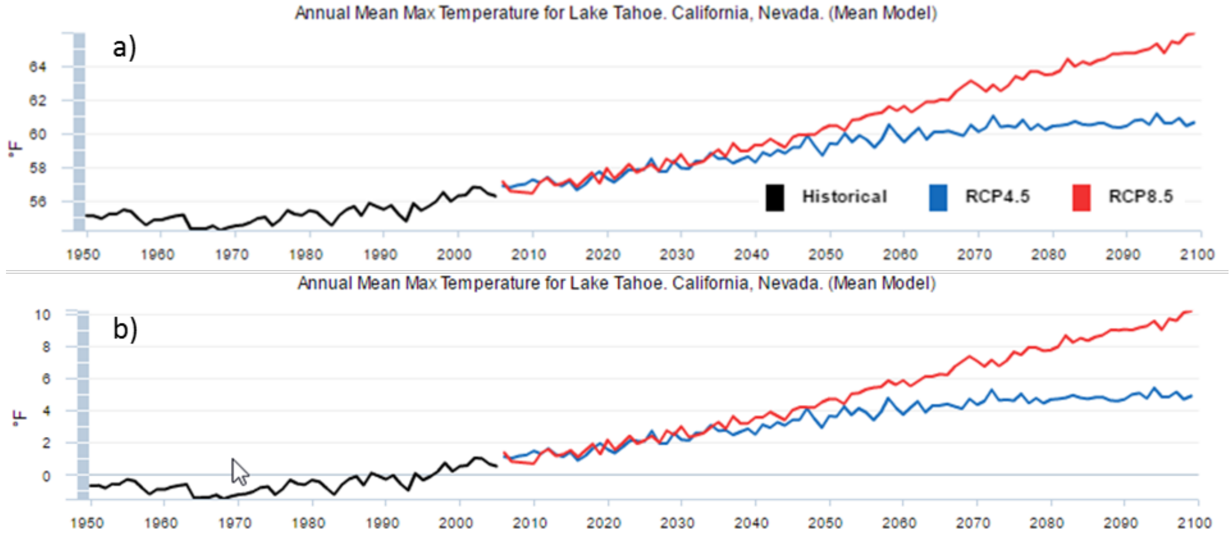


Figure 14. Mean model output for 30 models from CMIP5 Max air temperature time series showing historical (baseline) and future RCP4.5, RCP8.5. a) max air temperature values and b) relative change in max air temperature, in degrees Fahrenheit.

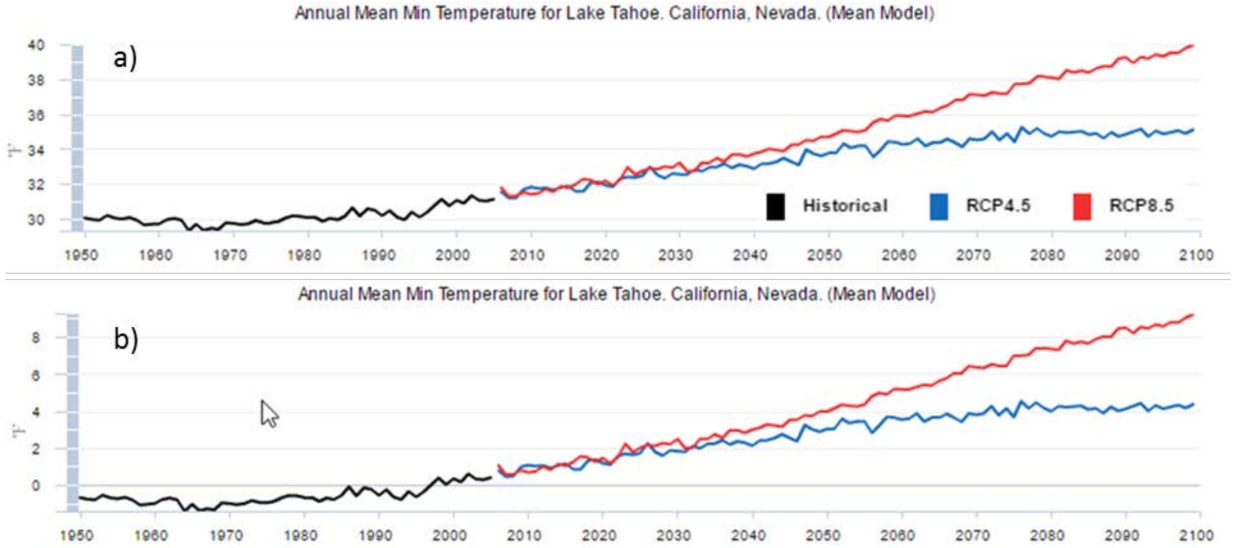


Figure 15. Mean model output for 30 models from CMIP5 Min air temperature time series showing historical (baseline) and future RCP4.5, RCP8.5. a) min air temperature values and b) relative change in min air temperature, in degrees Fahrenheit..

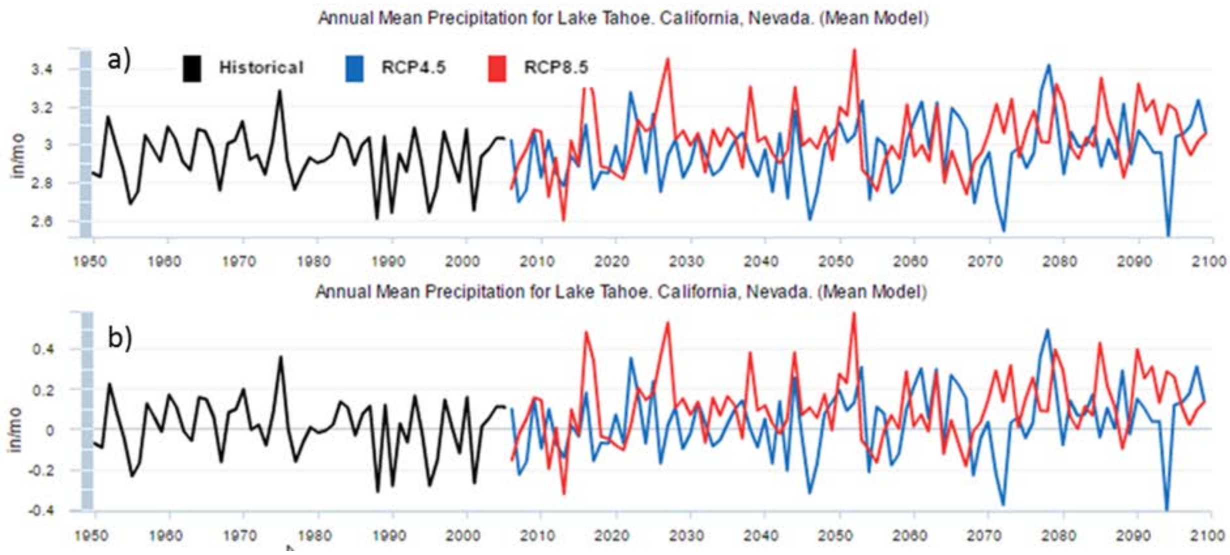


Figure 16. Mean model output for 30 models from CMIP5 precipitation time series showing historical (baseline) and future RCP4.5, RCP8.5. a) precipitation values and b) relative change in precipitation, in inches per month. Note that the historical precipitation data was developed by Hostetler and Adler, 2016 and Moss *et al.*, 2010 and is based on a bias-corrected climate simulation.

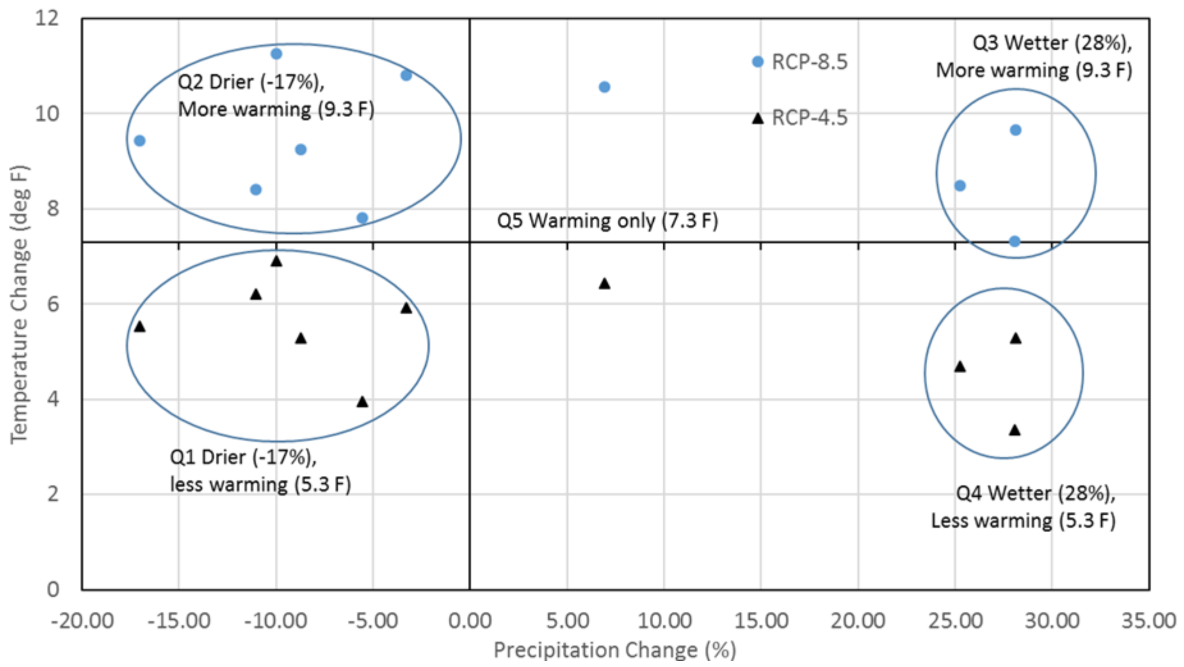


Figure 17. The five GCM-based scenarios of climate change run to assess impact on recharge and groundwater levels.

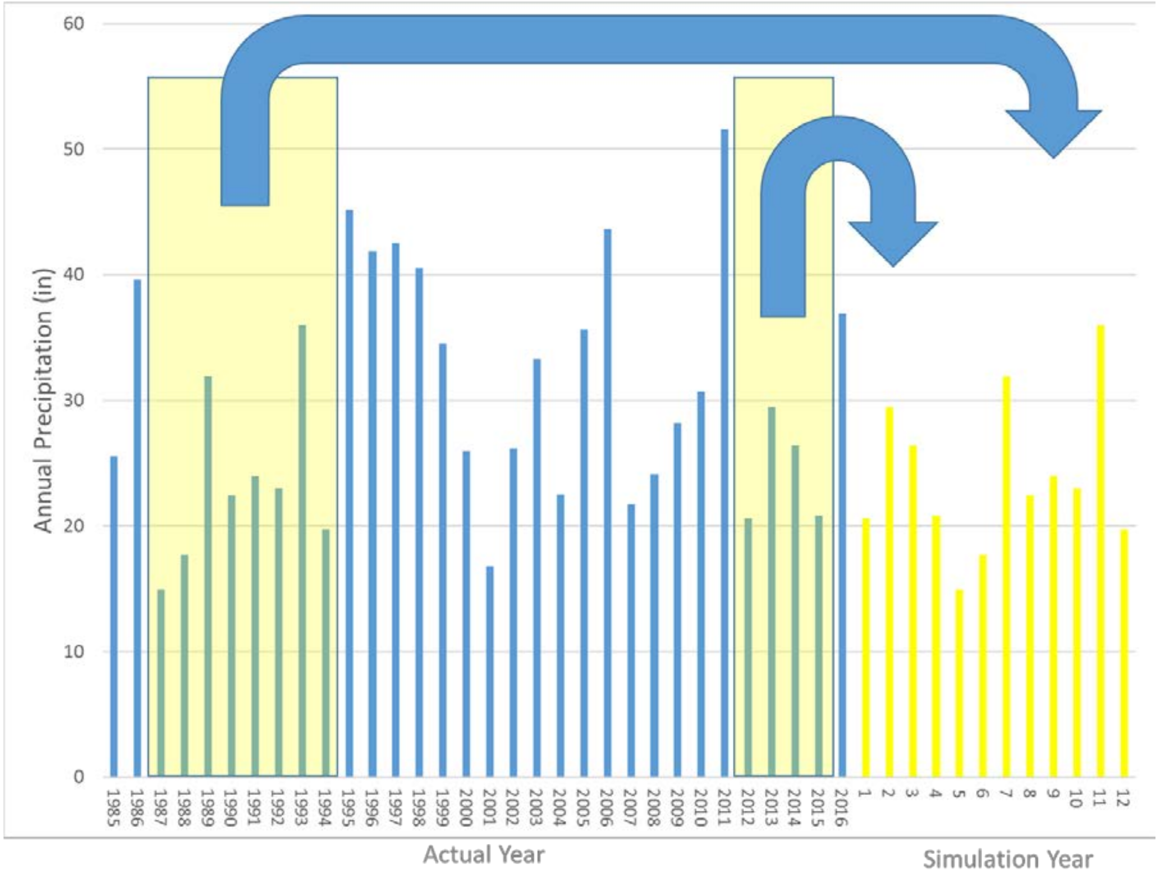


Figure 18. Historical and simulated precipitation at Hagan's Meadow for drought scenario (Q6). Data are compiled by piecing together 2012-2015 and 1987-1994 droughts to create a 12 year drought scenario.

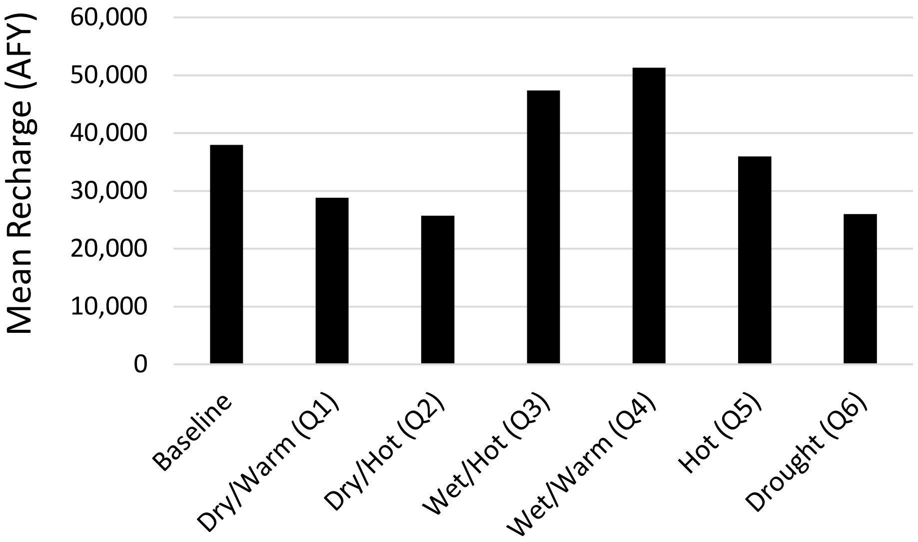


Figure 19. Simulated recharge amounts for the baeline and six climate scenarios.

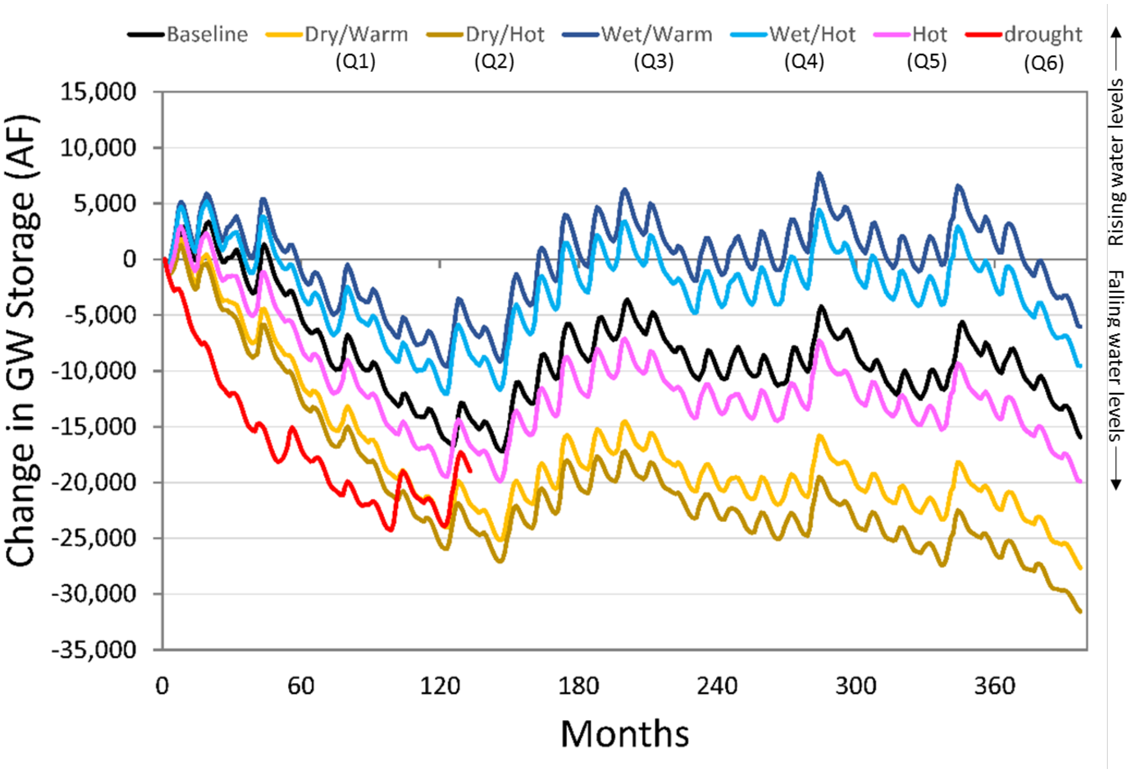


Figure 20. Average change in groundwater storage within the Tahoe Valley South groundwater basin for the baseline simulation and six climate scenarios.

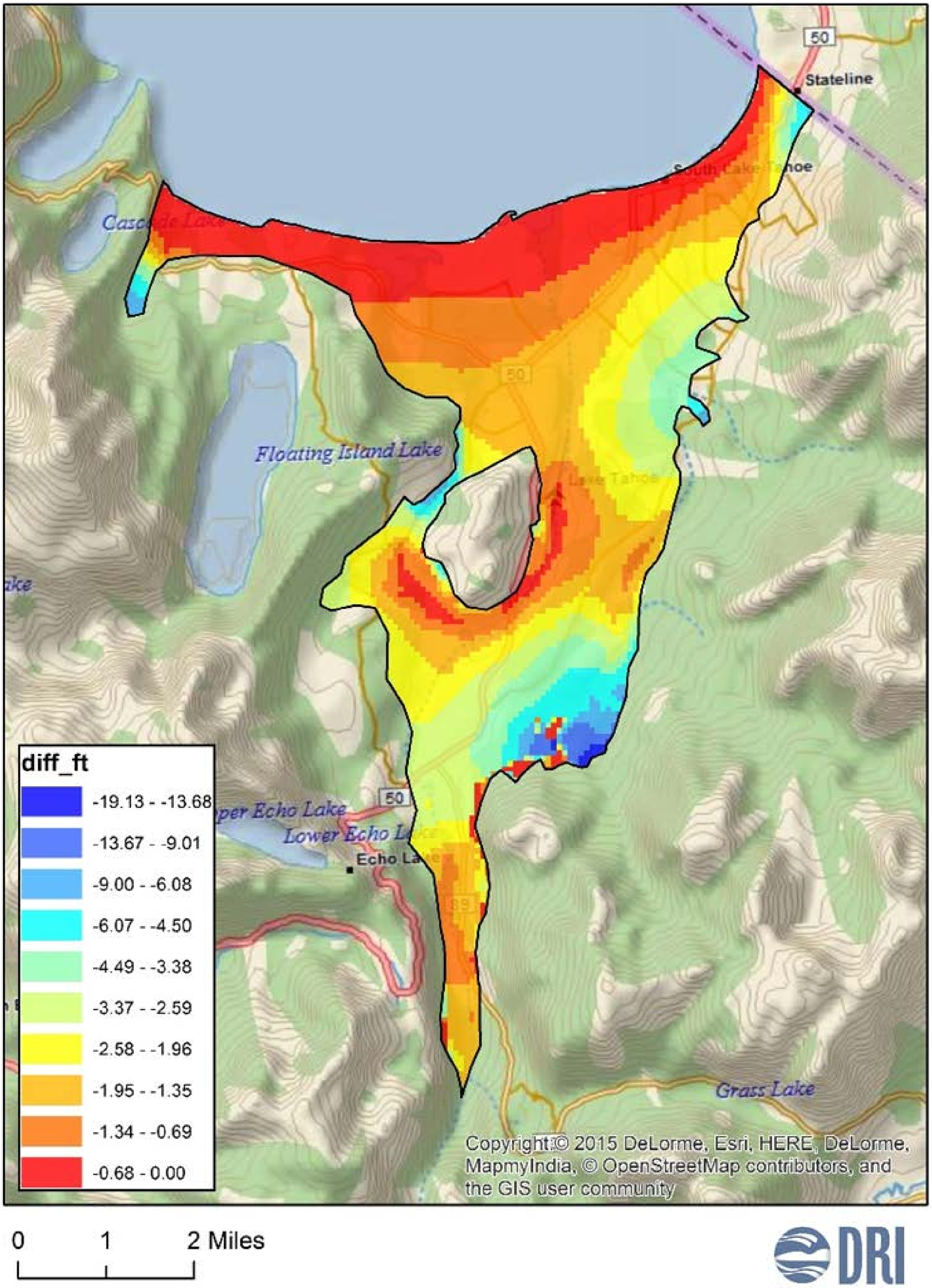


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Figure 21. Simulated changes in groundwater levels between the baseline and Scenario Q4 (warmer/wetter) at the end of the 33 year simulation. Negative water level changes indicate rising water levels relative to historical conditions.

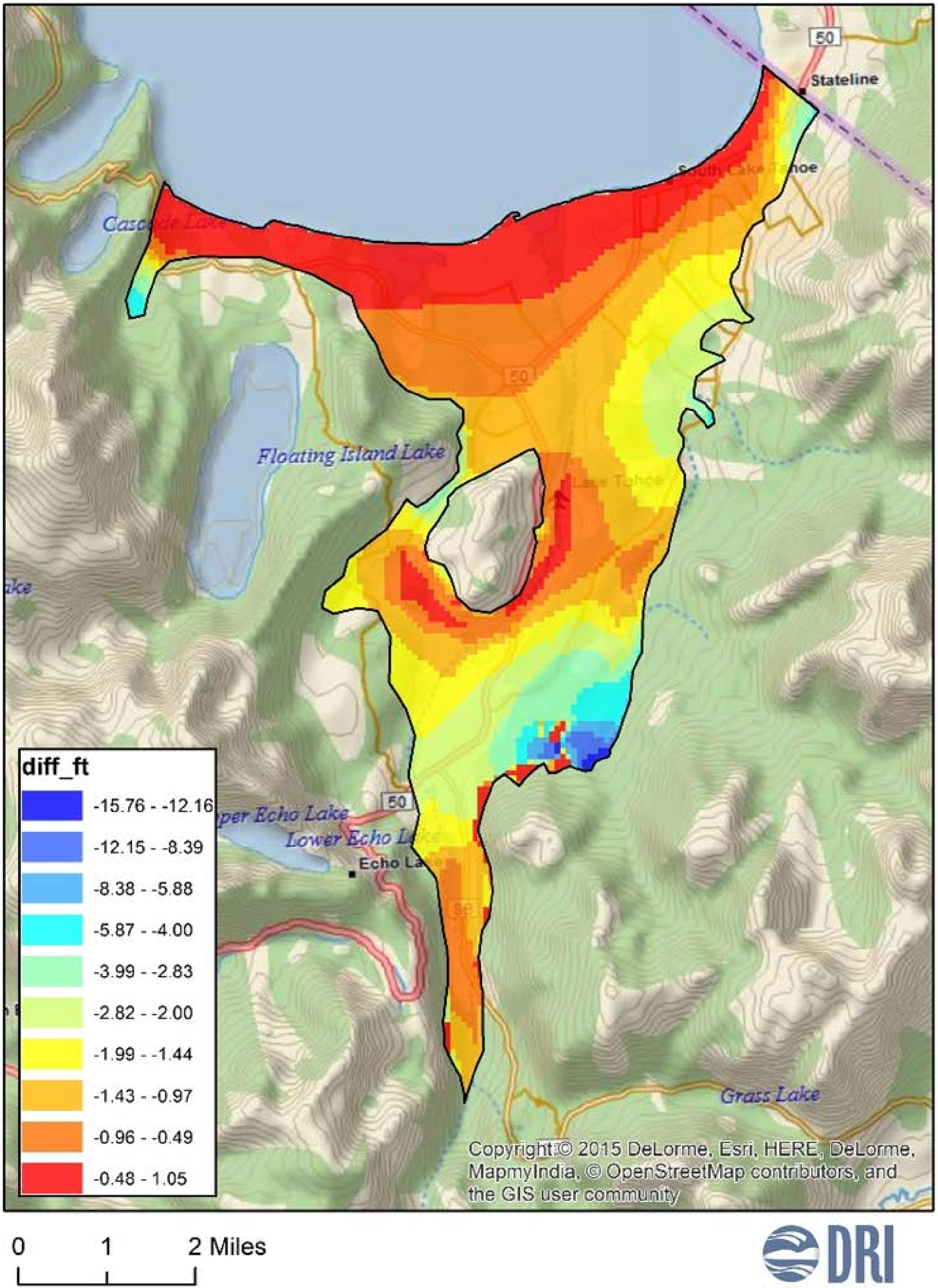

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Figure 22. Simulated changes in groundwater levels between the baseline and Scenario Q3 (hot/wetter) at the end of the 33 year simulation. Negative water level changes indicate rising water levels relative to historical conditions.

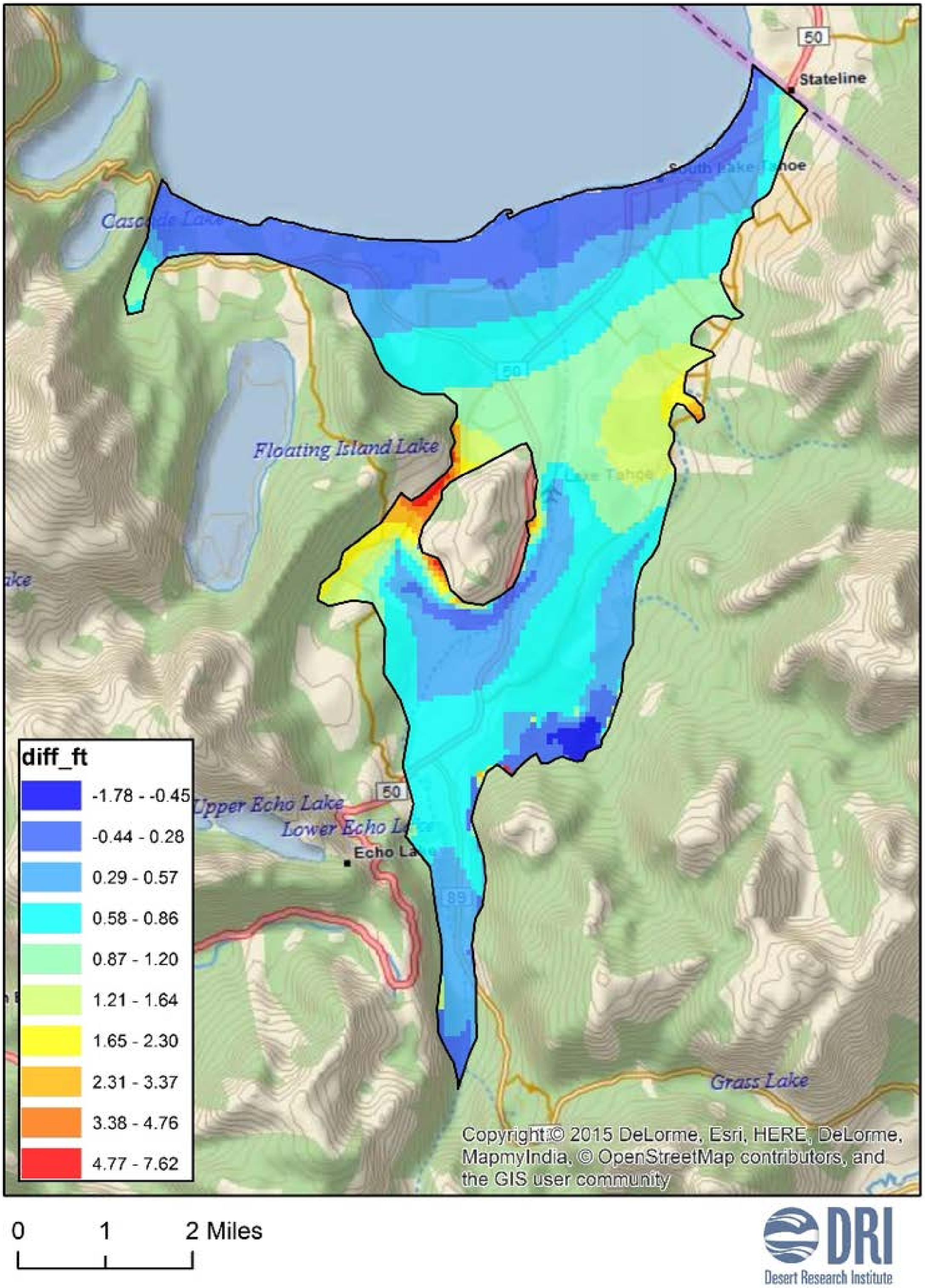

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Figure 23. Simulated changes in groundwater levels between the baseline and Scenario Q5 (warming only) at the end of the 33 year simulation. Negative water level changes indicate rising water levels relative to historical conditions.

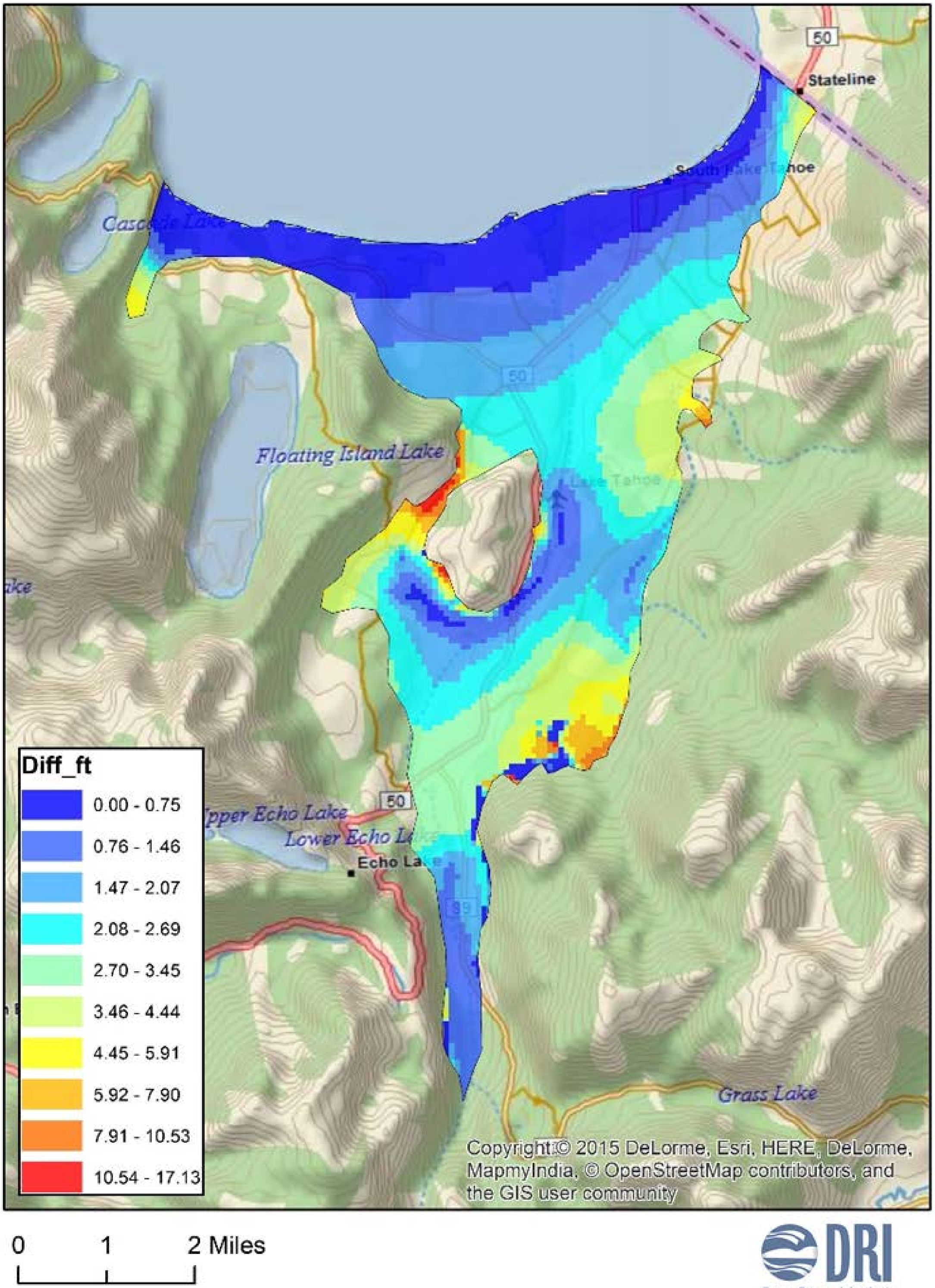

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Figure 24. Simulated changes in groundwater levels between the baseline and Scenario Q1 (warmer/dryer) at the end of the 33 year simulation. Negative water level changes indicate rising water levels relative to historical conditions.

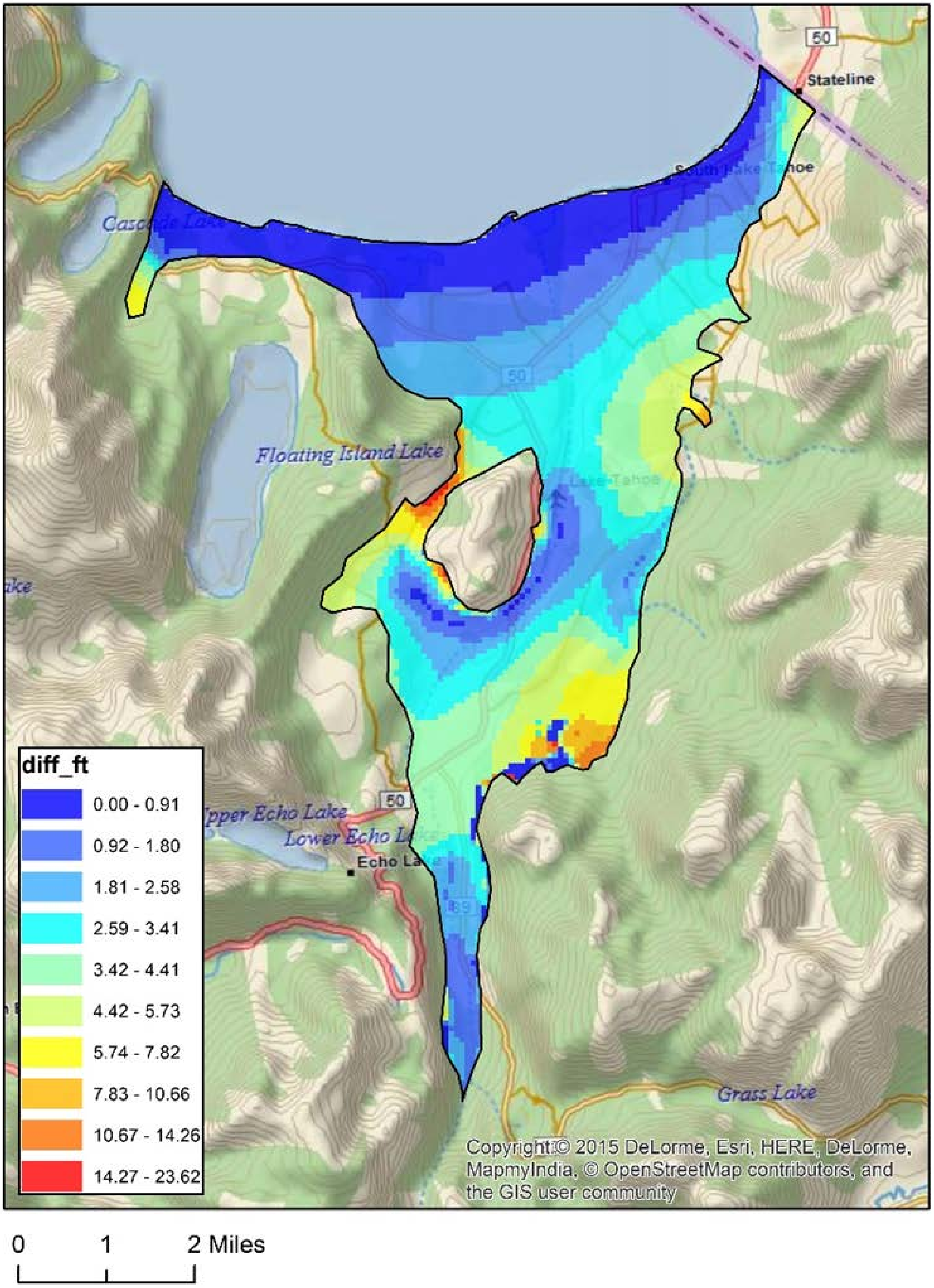


Figure 25. Simulated changes in groundwater levels between the baseline and Scenario Q2 (hot/dryer) at the end of the 33 year simulation. Negative water level changes indicate rising water levels relative to historical conditions.

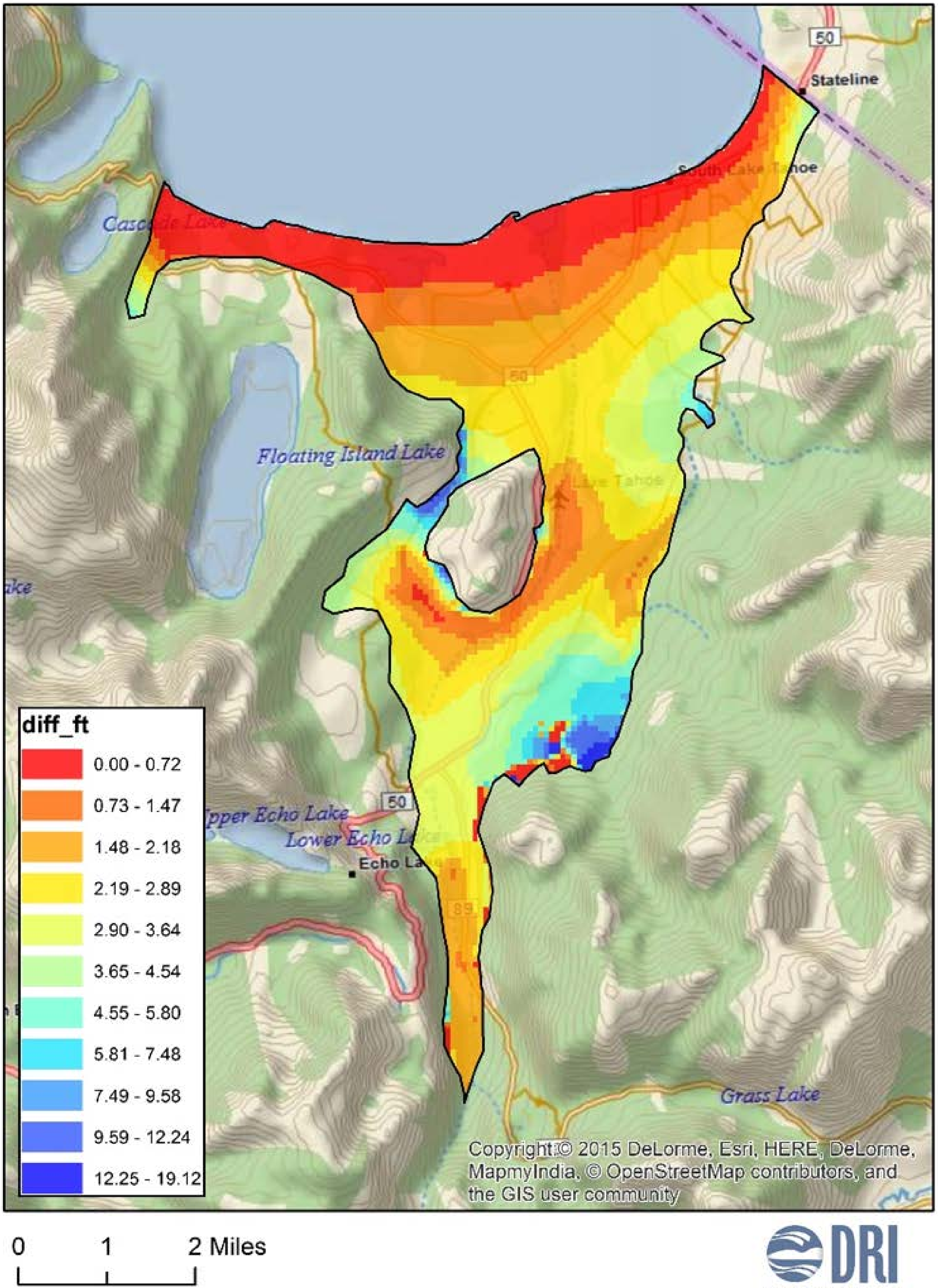
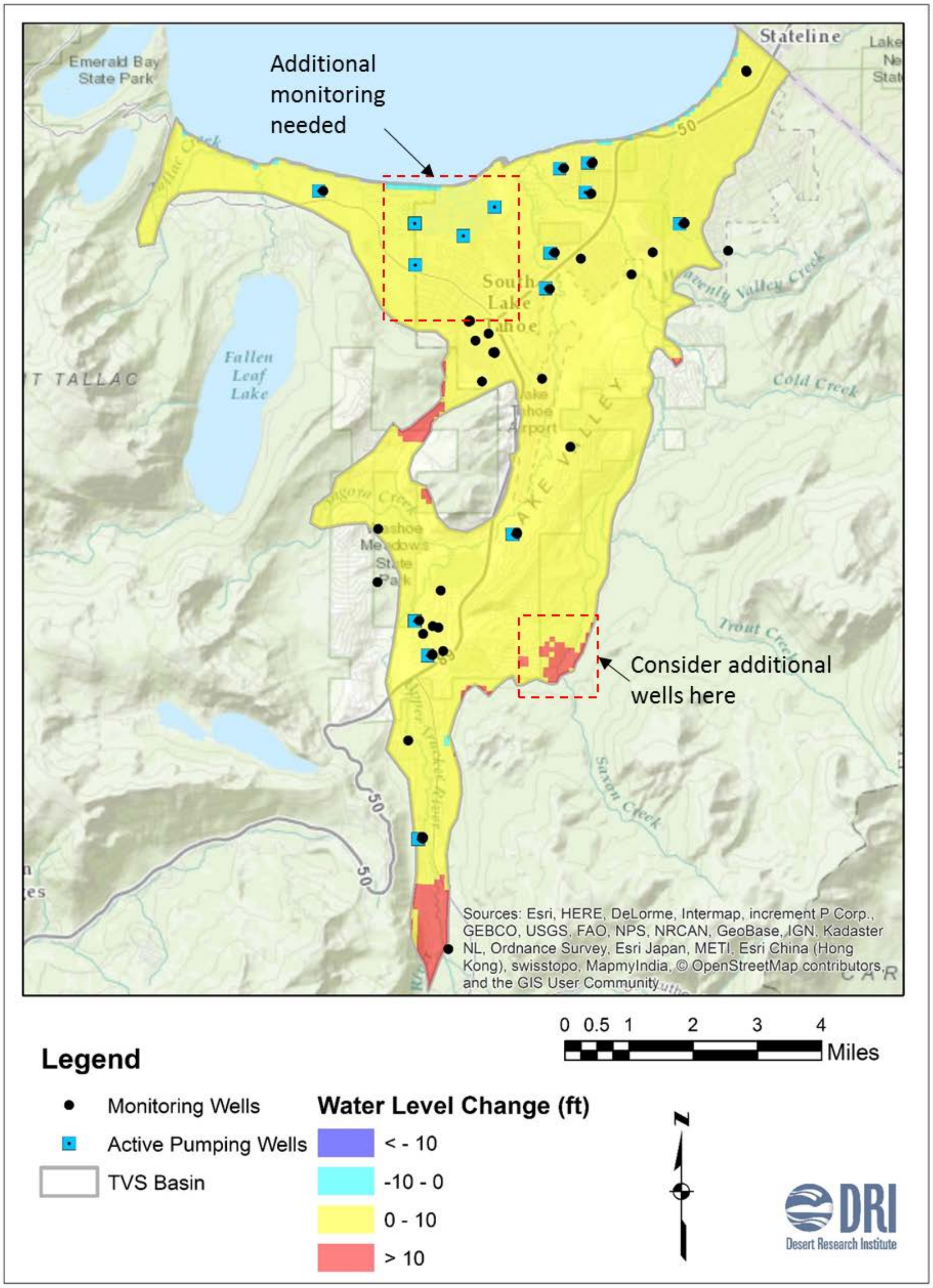


Figure 26. Simulated changes in groundwater levels between the baseline and Scenario Q6 (drought) at the end of the 12 year simulation. Negative water level changes indicate rising water levels relative to historical conditions.



Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 27. Existing monitoring well locations, active pumping wells, and simulated changes in groundwater levels between the baseline and Scenario Q2 (hot/dryer) at the end of the 33 year simulation. The region where additional monitoring is being proposed is shown in red dashed square region. Negative water level changes indicate rising water levels relative to historical conditions.

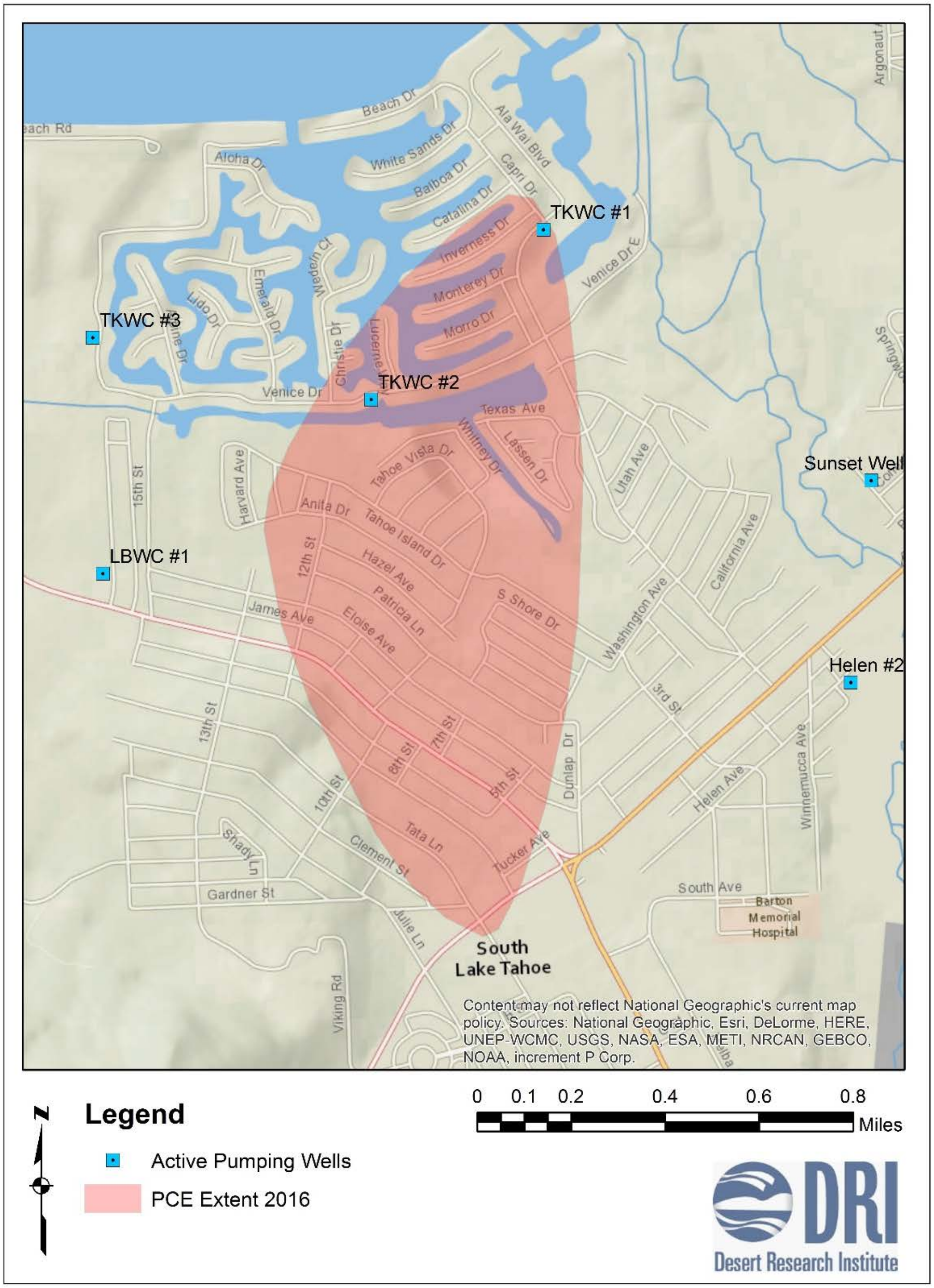


Figure 28. Extent of measureable PCE concentrations in 2016. Also shown are active pumping wells.