Desert Research Institute

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South Lake Tahoe Groundwater Model

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1. Introduction

The South Tahoe Public Utilities District (STPUD, or District) recently developed an updated groundwater management plan (GMP; STPUD, 2014) for the Tahoe Valley South (TVS) groundwater basin listed by the California Department of Water Resources (DWR) as Groundwater Basin 6-5.01 (DWR 2003; DWR 2004). The TVS groundwater basin is comprised of an alluvial aquifer which supplies approximately 95% of the drinking water to the area with groundwater pumping estimated at 7,770 AFY (this report) to service a seasonally fluctuating population ranging from 25,000 to more than 70,000 (Fogg et al. 2007). The aquifer contains a sequences of sand and gravel intermixed with confining units of clay and silt of localized extent (Fogg et al. 2007). Snowmelt in the surrounding Sierra Nevada Mountains and Carson Range provide the majority of recharge into the TVS aquifer with spatial and temporal distribution of recharge highly dependent on precipitation type and timing and likely susceptible to climate change in the future. The GMP identifies the maintenance of a sustainable groundwater supply as a best management objective with a call to use alternative hydrologic methods to estimate groundwater recharge to improve estimates of groundwater inflows and outflows for the TVS basin.

1.1. Previous Models

Significant research has occurred in the Tahoe Basin to characterize geology, hydrogeology, water quality and expected climate change impacts on water resources (e.g. Burnett 1971; Rowe & Allander 2000; Jeton 1999; Bales et al. 2006; Dettinger 2013; Coats et al. 2013; USACE 2003). Two contemporary numeric models overlap the TVS groundwater basin and are highlighted based on relevance to this project. The STPUD groundwater model developed by Fogg et al. (2007) was constructed in MODFLOW-2000 (Harbaugh et al. 2000) to help the District consider future groundwater development options and determine vulnerability of existing and proposed wells to possible contamination. This model is referred to as the South Tahoe Groundwater Model, or STGWM. The modeled domain (Figure 1) is limited to the extent of the alluvial aquifer (103 km^2; 40 mi^2) and is simulated at a relatively fine model grid-resolution (66 m; 200 ft). Complex alluvial stratigraphy, representative of 26 water-bearing units, are simulated with 11 model layers and 29 hydraulic zones. The range in calibrated hydraulic conductivity spans 0.003 m/d (0.0098 ft/d; silt) to 15.2 m/d (49.9 ft/d; coarse sand). Specific storage ranges from 0.004 to 1e-5, while specific yield varies from 0.11 to 0.2.

The second model considered was developed by the Desert Research Institute (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 U.S. Geological Survey (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 (Figure 1). This model is hereby referred to as the GSFLOW Regional Model, or GSFRM. The GSFRM encompasses 2,338 km^2 with a grid structure at 300 m (990 ft). Hydrostratigraphic units are represented with four model layers: two describing the alluvium and two bedrock. Model layer thicknesses are based on spatially interpolated well logs and thus variable but hydraulic properties are held constant across each layer. Hydraulic conductivity for the alluvium is on the order of 1 m/d, while the bedrock ranges from 0.1 m/d (shallow) to 0.005 m/d (deep). Specific yield is specified at 0.1 and 0.005 for the alluvium and bedrock, respectively.

For calculations of recharge, the GSFRM is parameterized from the National Elevation Dataset (NED), 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 m grid. Five categories of LULC are used in each 300 m grid-cell based on dominant vegetation category: bare soils, grasses, shrubs, trees, and water. For the category water, recharge is assumed zero. The GSFRM simulates transient conditions from 1980 to 2014. A two year warm-up period is used to remove the influence of initial conditions. Daily weather data from four SNOTEL sites (Echo Peak, Fallen Leaf Lake, Hagans Meadow and Heavenly Valley) are used to drive the model in the region of the TVS groundwater basin. While stations give point climate, Parameter-elevation Regressions on Independent Slopes Model (PRISM, OSU, 2012) maps 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.

1.2. Objectives of Current Study

The objective of this study is to calculate a water budget for the TVS groundwater system in which annual water budget terms are established for water years 1983 to 2014. The approach combines the geologic complexity represented in the STGWM; with the energy-water budget calculated recharge from the GSFRM, into comprehensive models for the TVS Basin.

1.3. Model Selection

The TVS groundwater model construction and parameterization (i.e. recharge) relies on two numeric codes. These are described below.

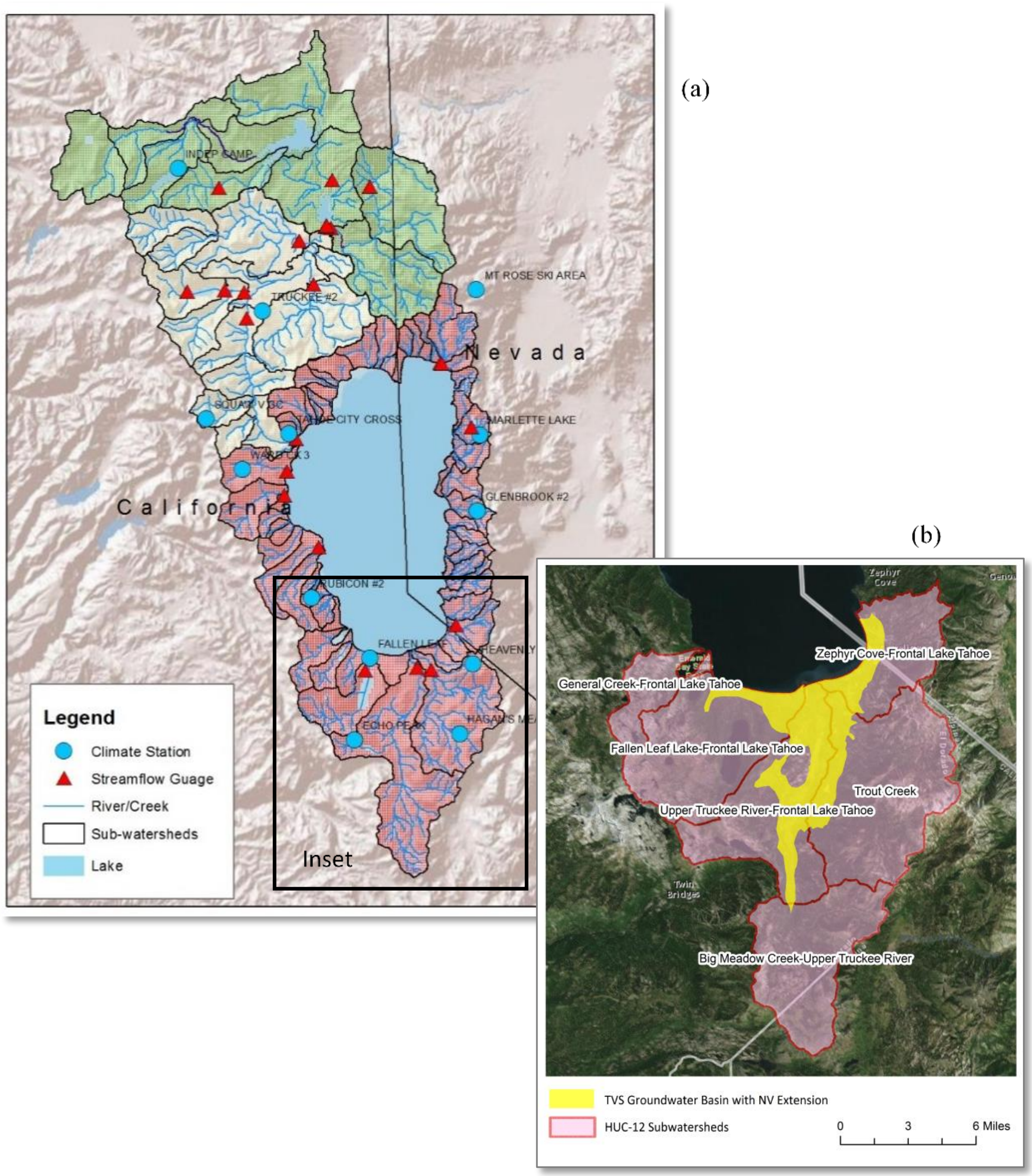

Figure 1: A comparison of modeled domains. (a) GSFRM highlighted in red with associated climate stations and streamflow gages used in its development, (b) Inset detail showing the extent of the TVS model domain as defined with HUC-12 watersheds, and the TVS groundwater basin simulated with the STGWM with an extension into NV.

1.3.1. MODFLOW-NWT

MODFLOW (Harbaugh et al. 2000; Harbaugh 2005) relies on the finite difference numerical method to obtain approximate solutions to the groundwater flow equation, in which a continuous system is broken into discrete points in both space and time, and partial derivatives are replaced by the differences in head between these discrete points at the center of each block or cell. MODFLOW-NWT (Niswonger et al. 2011) 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 (Knoll and Keyes, 2004). 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 UPW package replaces the traditional MODFLOW packages, including the block-centered flow (BCF), the layer-property flow (LPF), and the hydrogeologic-unit flow (HUF). The UPW package differs from these previous packages by smoothing the horizontal-conductance function and the storage-change function during wetting and drying to provide continuous derivatives for the solution by the Newton method, as opposed to a linear approach to their calculation. Model development, parameterization and calibration are described in sections 3-5 of this report.

1.3.2. GSFLOW

GSFLOW accounts for flow within and between three regions: (1) the plant canopy to the bottom of the soil zone; (2) the surface water bodies; and (3) the groundwater system below the soil zone. PRMS is used to model the first zone and MODFLOW accounts for flows through the second and third zones. Water and energy balances are computed daily using climatic inputs (temperature, precipitation) to estimate various sub-components of evapotranspiration (ET); including soil and plant transpiration, snow sublimation, canopy interception and groundwater ET, interflow, runoff, groundwater recharge and surface-groundwater interaction. GSFLOW allows for complex linkages between climate, land use and geology to better understand spatial and temporal hydrologic partitioning at watershed scales.

2. Site description

2.1. Location

The TVS groundwater basin (Figure 1) represents the largest and most productive groundwater basin within the Lake Tahoe hydrologic basin (STPUD 2014). It resides principally in El Dorado County, California with a portion of the basin extending eastward into Nevada, and is bounded on the southwest by the Sierra Nevada Mountains and on the southeast by the Carson Range. Lake Tahoe boarders the northern edge of the TVS groundwater basin. The Lake Tahoe average elevation is 1,898.6 m (6229 ft, NAVD 88) given daily stage recordings from 1960-present and provides relative stability to alluvial water levels in area. The City of South Lake Tahoe occupies the northern portion of the basin. Elevations in the TVS domain range from 1,876 m to 3,296 m (10,813 ft) on the summit of Freel located in the Carson Range. Six watersheds (HUC-12) were used to delineate the TVS model domain: General Creek (8.79 mi^2), Fallen Leaf (31.6 mi^2), Upper Truckee River (30.0 mi^2), Big Meadow Creek (27.4 mi^2), Trout Creek (40.7 mi^2) and Zephyr Cove (17.46 mi^2).

2.2. Climate

The Tahoe Basin climate is considered humid, continental. This characterization means cold, wet winters and warmer, drier summers. On average, minimum temperatures at the South Lake Tahoe Airport (NWS COOP 048762, elevation 1905 m; 6250 ft) range from -8.8ºC (16.2ºF) in December to 5.4ºC (41.7ºF) in July, while maximum daily temperatures range from 5.1ºC (41.2ºF) in January to 26ºC (78.8ºF) in August. Most precipitation falls as snow, though rain-on-snow events do occur that can cause substantial flooding. Amount of precipitation is strongly controlled by elevation with average annual totals of 41 cm (16.14 in) at the airport to 147 cm (57.9 in) at Echo Park SNOTEL (ID: 463; 2338 m; 7671 ft) but with a decreasing trend as one moves west to east. For example, annual precipitation at the Heavenly SNOTEL (ID: 518; elevation 2615 m; 8579 ft) located near the California-Nevada state line is higher in elevation than the Echo Park SNOTEL but receives significantly less precipitation at 84 cm (33 in). The area has experienced several periods of drought. Focusing on water years since 1984, significant droughts have occurred during the intervals of 1987-1992, 2000-2004, 2007-2010 and 2012-2015. While water year 2015 is not simulated, it represents the lowest precipitation on record with most most NRCS SNOTEL sites in the vicinity of the TVS groundwater basin reporting 57% to 75% of the period of record average annual precipitation.

2.3. Geology

The geology of the TVS groundwater basin is primarily comprised of Mesozoic granitic rocks in the mountainous portions of the basin, while Quaternary aged glacial deposits and alluvium occupy the lower portions of the basin (Jennings 1977; Ludington et al. 2005). Small localized pockets of Mesozoic volcanic and metamorphic rock occur in the mountains southwest of Fallen Leaf Lake while Jurassic Marine deposits occur east of Fallen Leaf Lake Extensive subsurface geologic mapping of the alluvial fill was conducted by (Fogg et al. 2007) and implemented into the STGWM. In general, highly permeable units occur in the glacial outwash, fluvial and deltaic deposits are identified as excellent groundwater aquifers and reside primarily on the north side of the basin. At least four fine-grained lake deposits containing silt and clay occur to produce confined and semi-confined units based on areal extent and permeability.

3. Model Development

The model domain is defined by the topographic divide of those hydrographic basins contributing to the TVS groundwater basin (refer to Figure 1) with model grid, and layering described below.

3.1. Alluvium

Alluvial thickness is based on the STGWM and extrapolated across the entire TVS domain (Figure 2). Alluvial thickness exceeds 330 m (1,082 ft) to the vicinity of the Tahoe Marsh and thins to the south as it wraps around the eastern edge of Twin Peaks. A thick alluvial package is also observed to the southwest of Twin Peaks. The alluvium tends to taper as it moves toward its outer perimeter. In addition, alluvium is assumed to occur where streams exist. The thickness is most likely relatively thin (e.g. <10 m; 32 ft); but for modeling purposes is assigned to the full thickness of layer 1 (40 m, 141 ft). The areal extent is limited to the stream corridor to mimic that modeled in the GSFRM model.

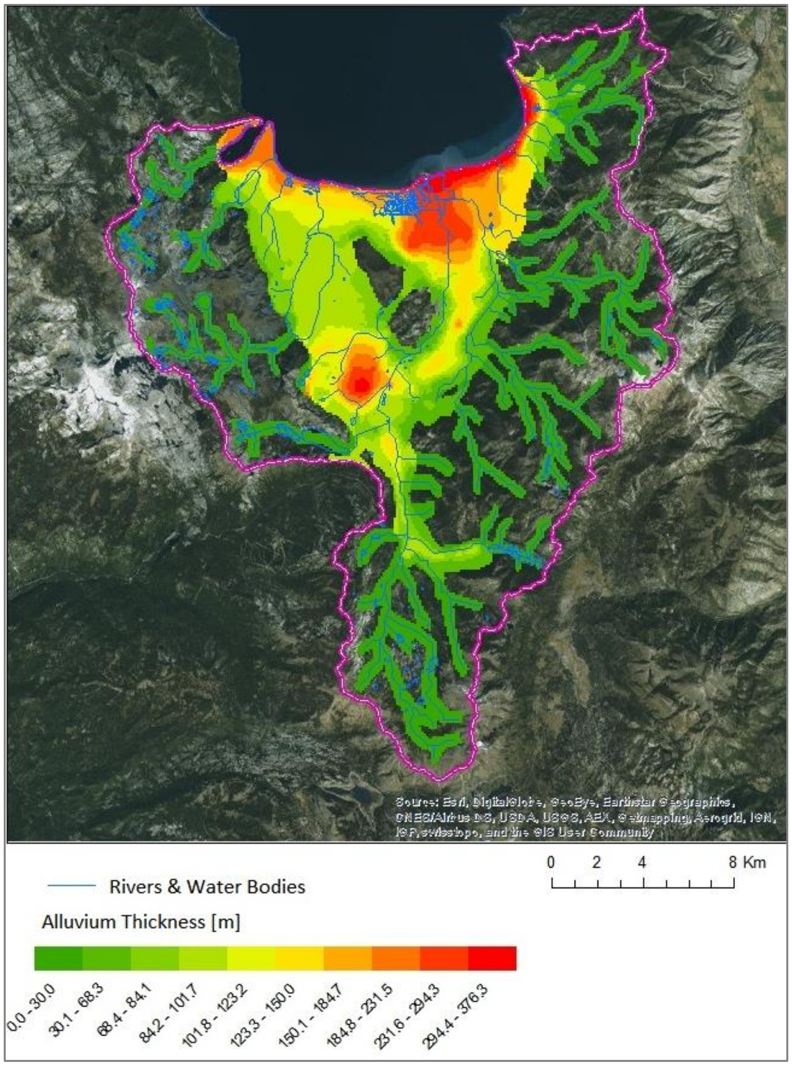

Figure 2: Alluvial thickness modeled in the TVS groundwater model. Thickness obtained from the STGWM and extrapolated across the domain. Thin alluvium also assumed to exist along river corridors.

3.2. Grid and Layering

Figure 3 compares the grid resolution of the GWFRM (300 m; 984 ft) and the smaller scale TVS (100 m; 328 ft). The TVS grid is oriented north-south and contains 342 rows and 251 columns. The lower left corner of the grid is located at east 745800.0 and north 4287900.0 given NAD83 UTM zone 10. Cell size is based on the need to capture steep topography, narrow canyons and potentially steep hydrologic gradients. The increased areal coverage over the STGWM allows a robust estimate of a spatially and temporally varying mountain block recharge while maintaining numeric stability and reduced computational time.

The TVS groundwater model is limited to four layers to maintain reasonable computation time. Layers are determined from visual clustering of production well screen intervals wells in the basin (Figure 4). Land surface elevations are based on 30 m DEM aggregated to a 100 m resolution. Layer thicknesses are 40 m (131 ft) for layer 1 and layer 2; 100 m (328 ft) for layer 3. Layer 4 bottom elevation is set to a constant 1600 m (5,248 ft) to produce variable thickness ranging from approximately 114 m (274 ft) along the northern boundary with Lake Tahoe to 1300 m (4,264 ft) at watershed divides. Land surface elevations and an example of layering and zonation of principal lithology between bedrock and alluvium is

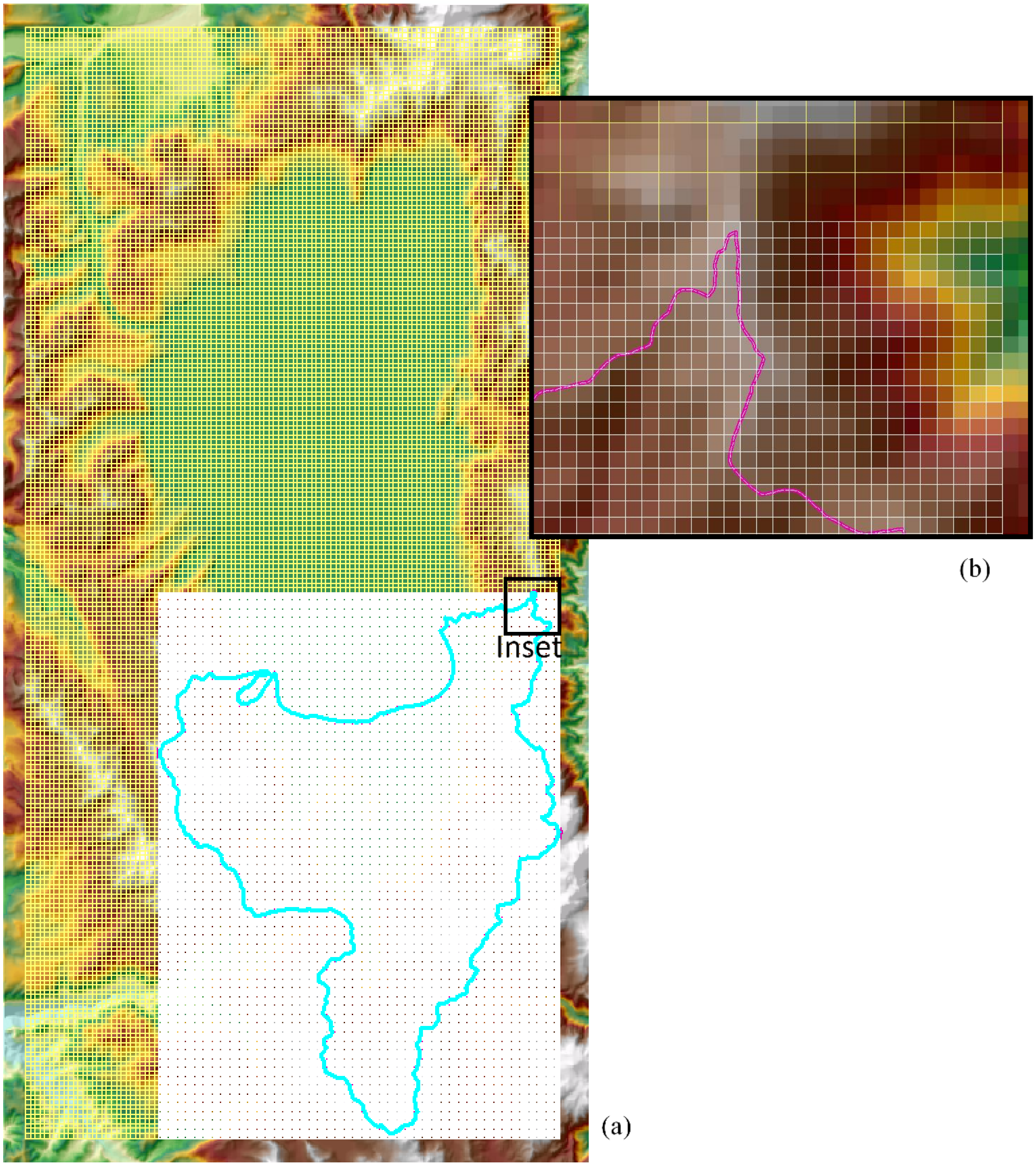

Figure 3. (a) A comparison of grid resolution between GSFRM at 300 m and TVS at 100 m. Figure includes the 100 m DEM and TVS groundwater domain; (b) inset detail showing edge of TVS groundwater domain (pink) with grid overlay.

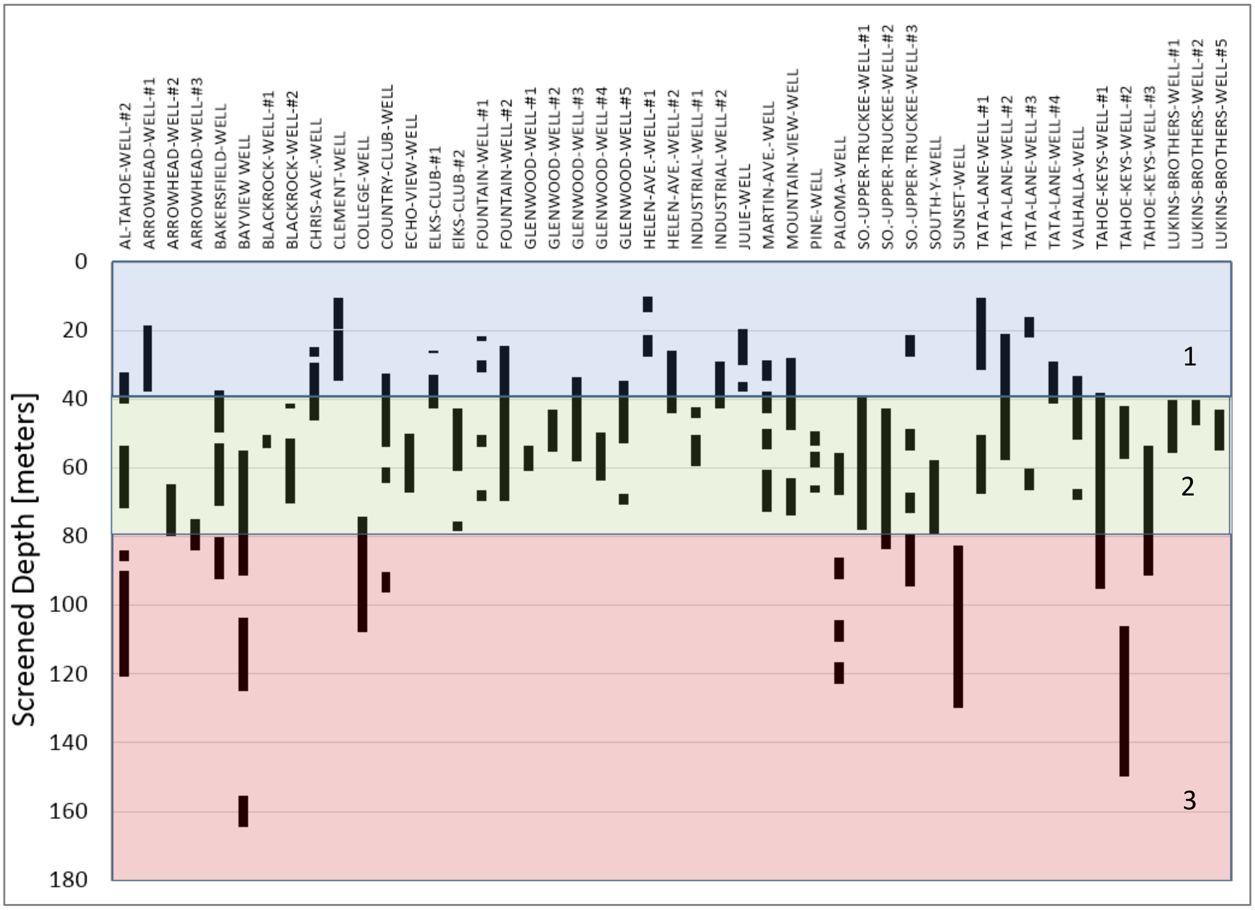

Figure 4: Production well screened intervals and associated modeled layer thicknesses. Layer 4 extends to a constant elevation of 1,600 m (5249 ft) with thickness variable between 114 – 1300 m (377 – 4265 ft)

provided in Figure 5. The assignment is determined by which lithology occupies more than 50% of cell by thickness.

4. Steady State Model Parameterization and Results

The steady state model calibration is done to establish the hydraulic conductivity fields and determine initial conditions in water level given pre-(significant) groundwater development in the basin. Boundary conditions of recharge, river baseflow, and groundwater flux to Lake Tahoe are defined as mean conditions with details on each provided below.

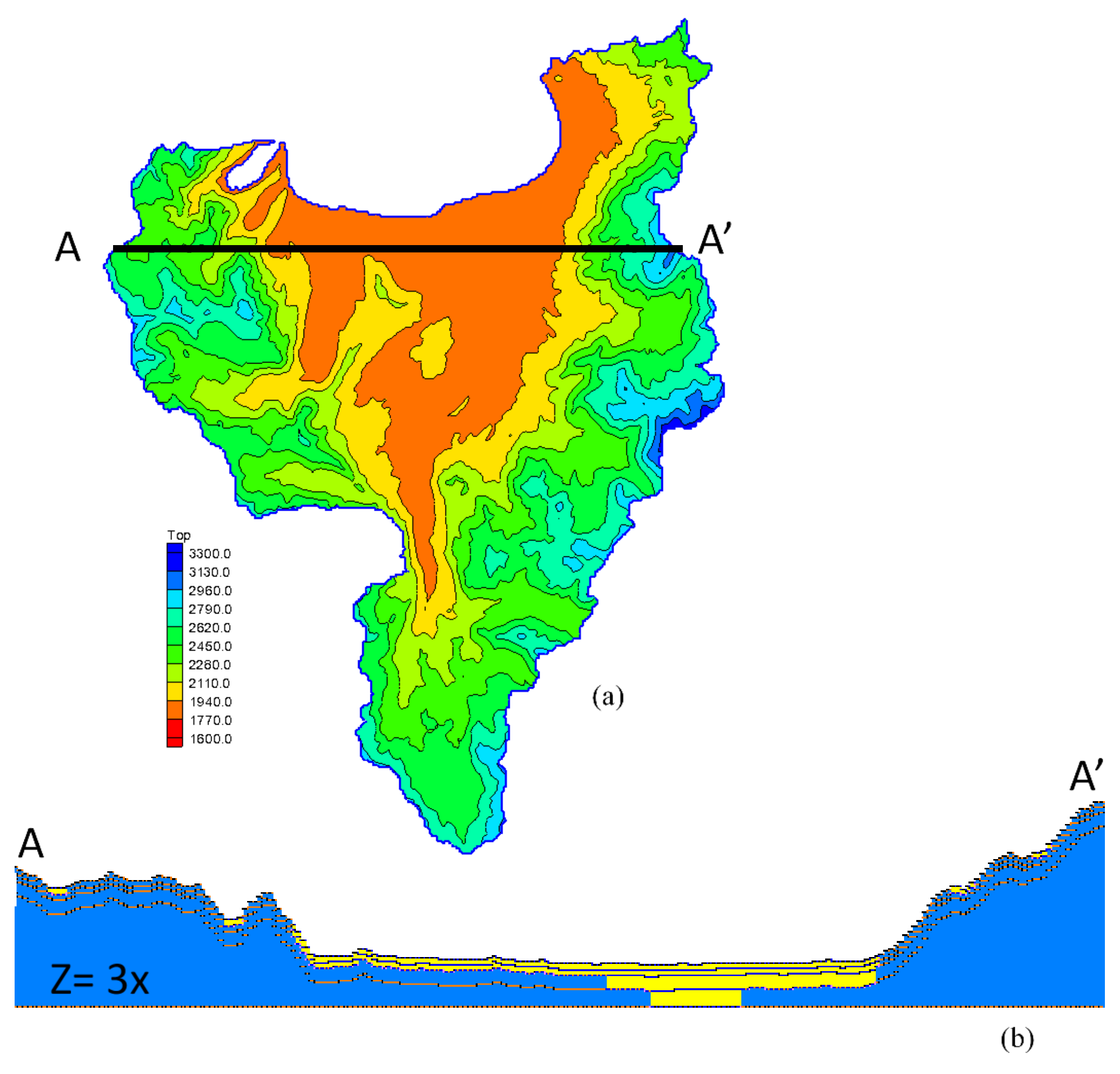

Figure 5: (a) Land surface elevations with cross section marked, (b) illustration of layering and assignment of principal lithology; bedrock in blue and alluvium in yellow.

4.1. Boundary Conditions

4.1.1. Recharge

Recharge was extracted from the GSFRM and applied to the TVS domain. 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 for the TVS hydrologic basin varies from year to year based on annual cycles of precipitation. The annual average recharge estimate from the GSFRM is approximately 42,000 AFY (note: determined by average of wy 1983-2011, or extent of GSFRM at the time of steady state model development) with most recharge occurring in the mountains of the Sierra Nevada and the Carson Range. The ratio of recharge computed by the

GSFLOW model to annual precipitation, which we term 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, or approximately 41 in/yr over the domain. Computed recharge efficiency for the TVS hydrologic basin varies annually but on average is approximately 12%, or 4.92 in/yr (0.41 ft/yr). The fraction of precipitation that becomes recharge is consistent with other studies in the region (Flint and Fline, 2007). The spatial distribution of steady state recharge based on average conditions is provided in Figure 6.

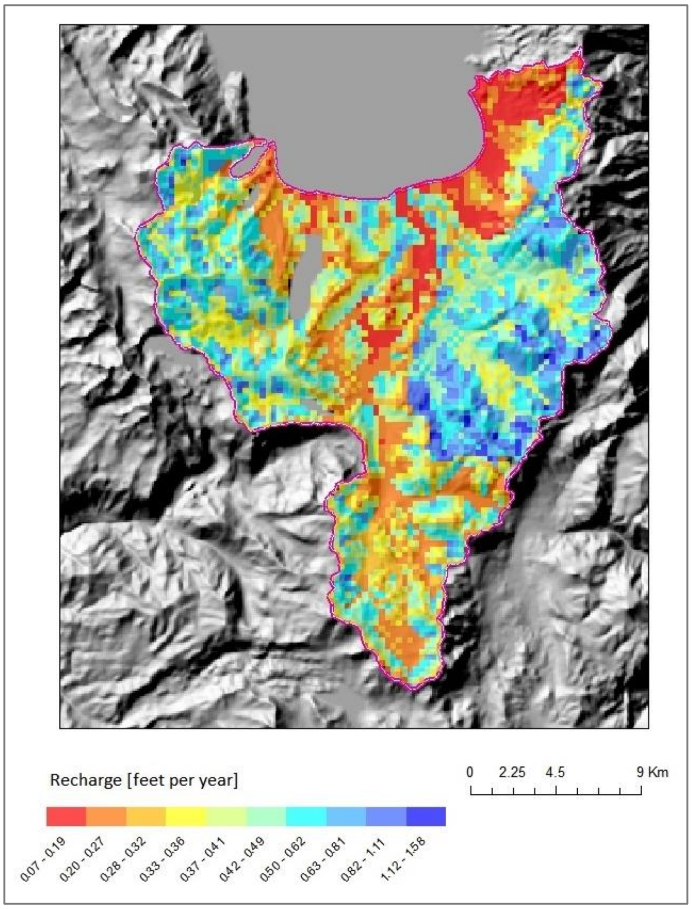

Figure 6: Steady state recharge distribution (ft/yr) extracted from the GSFRM.

4.1.2. Baseflow

Groundwater derived stream discharge is known as baseflow. Streams are modeled with the river package (RIV) in MODFLOW (Figure 7) with river bottom elevation defined using land surface elevations. Small lakes are not modeled explicitly in the TVS but assumed to be continuations of river flow. Stream discharge is calculated as the gradient driven net gain or loss in stream flow from groundwater interaction, with flow regulated through a conductance term. Stream discharge is very sensitive to recharge and relatively insensitive to the conductance term. Therefore, conductance for all stream reaches was set to 1.0 m^2/d/m (3.2 ft^2/d/ft). Observed stream discharge gages are identified in Figure 7. Observed baseflow was calculated as the mean stream discharge from August 1 through February 15 as determined from USGS daily statistics for the period of record for each gage. No calibration was required to match observed baseflow

4.1.3. Groundwater Flux to Lake Tahoe

Groundwater flux to Lake Tahoe is simulated using the General Head Boundary (GHB) package. Lake stage was set to 1898.6 m (6,229 ft; NAVD 88) to represent average Lake level from 1957 to 2002 for comparison to previously estimated flux of 3,972 acre-feet per year (AFY) for South Lake Tahoe including the Emerald-Taylor section (USACE 2003). The steady state model contains no groundwater pumping and the mean withdrawal from 1983 to 2014 is 7,780 AFY. If

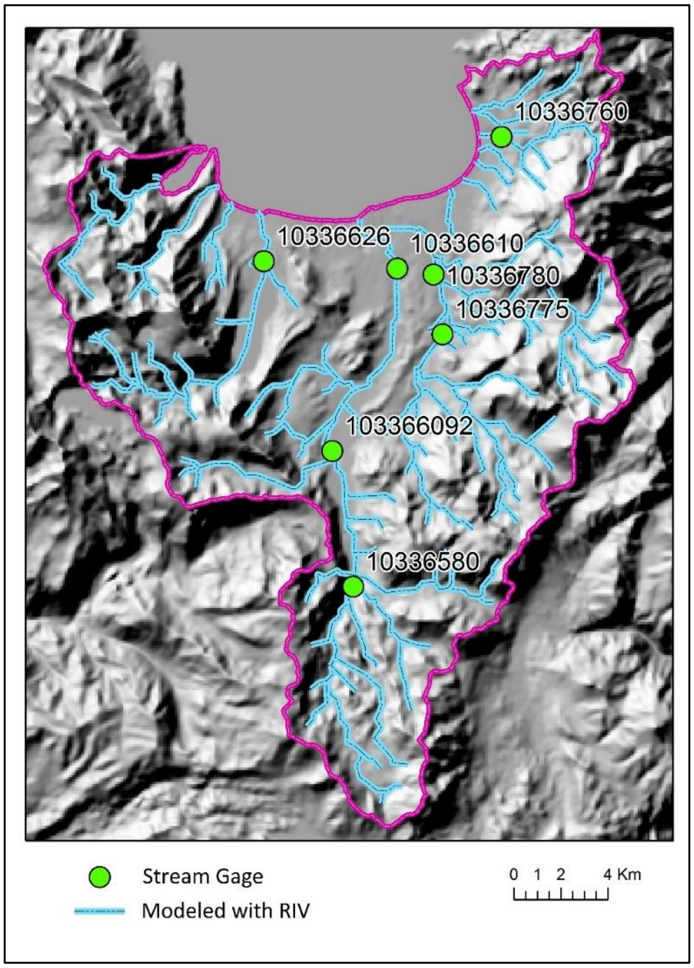

Figure 7: Stream reaches modeled with the RIV package with observation gages identified.

one assumes that all water pumped was destined for Lake Tahoe as groundwater discharge, then the adjusted groundwater flux to the Lake is 11,702 AFY. The GHB conductance term was then adjusted in conjunction with the hydraulic conductivity field (described below) to simultaneously match groundwater flux to Lake Tahoe and observed water levels.

4.2. Hydraulic Conductivity

4.2.1. Pilot Points

Characterization of geological heterogeneity used the pilot points methodology (Doherty 2008), in which observed hydraulic conductivity (K) were obtained for various boreholes (Figure 8) and assigned to the alluvial zone in the model. Observed mean values span from 0.14 m/d (0.46 f/d) to 63 m/d (207 ft/d) with the largest observed value associated with Arrowhead #2 located south of Twin Peaks. While most K-observations were held fixed, a few borehole K-values use observed values as a first-guess and are allowed to adjust to improve calibration to best match the initially observed water levels in several DWR wells. Specifically, those boreholes with K-values adjusted using PEST (Doherty 2008) during calibration include; South Upper Truckee Well #1A, Henderson Test well, Elks Club #2A. Blackrock Well #2, Bayview Well, Bakersfield Well and Arrowhead Well #2. Point K-values are spatially interpolated across the domain assuming inverse weighted-distance techniques. Alluvial K-fields are assumed to not change with depth. Bedrock K was determined through preliminary calibration using a zonal approach in which surface bedrock was assumed to have a unique value compared to bedrock at greater depth. These values are then held constant during subsequent pilot point calibration to establish lateral spatial variability within the alluvium.

Results

4.2.2. *Hydraulic Conductivity*

Calibrated, spatially distributed K-fields for layer 1 are provided in Figure 8. Bedrock K is 0.08 m/d (0.26 ft/d) in layer 1 and decreases to 0.0017 m/d (0.0056 ft/d) in deeper layers (2-4). Bedrock K is similar to those values used in the GSFRM of 0.1 m/d (0.32 ft/d) and 0.005 m/d (0.016 ft/d) with K values similarly decreasing with depth. Analogous to the STGWM, the TVS model predicts more permeable sediment extending from the Tahoe Marsh southward around the eastern edge of Twin Peaks. The TVS predicts very large K-values south of Twin Peaks on the order of 80 m/d (262 ft/d), but with observed mean in the Sioux Street Well reaching up to 65 m/d (213 ft/d), the calibrated value is deemed acceptable especially given the existence of gravel lithology in the TVS.

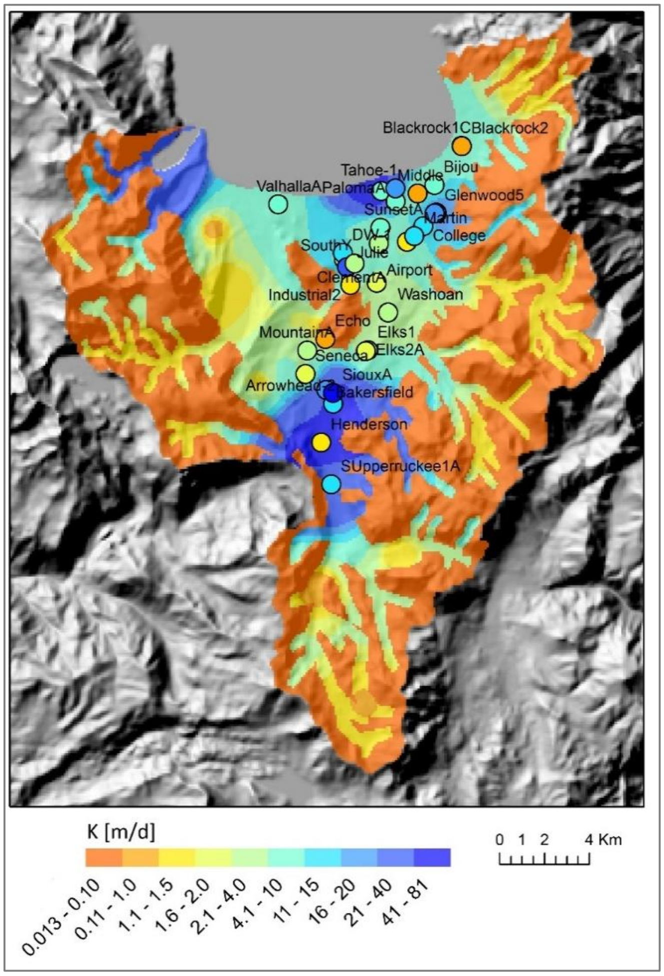

Figure 8: Hydraulic conductivity observed borehole data (circles) and calibrated field (areal).

4.2.3. *Water Levels*

Simulated and observed DWR water levels using in the calibration of the K-field are provided in Figure 9 showing excellent agreement; with a mean error (ME) of -1.5 m (2%), a mean absolute error of 1.97 m (2.7%) and a root mean squared error of 3.4 m (4.7%)

Spatial distribution of steady state water levels and associated depth to water (DTW) are provided in Figure 10. Predicted water levels in the alluvial portion of the domain are relatively flat ranging from 1890 m to 1950 m (6199 ft to 6396 ft) with water flowing northward toward Lake Tahoe but a groundwater divide is predicted to occur between Twin Peaks and Table Mountain as a result of the low K bedrock forming these mountain.

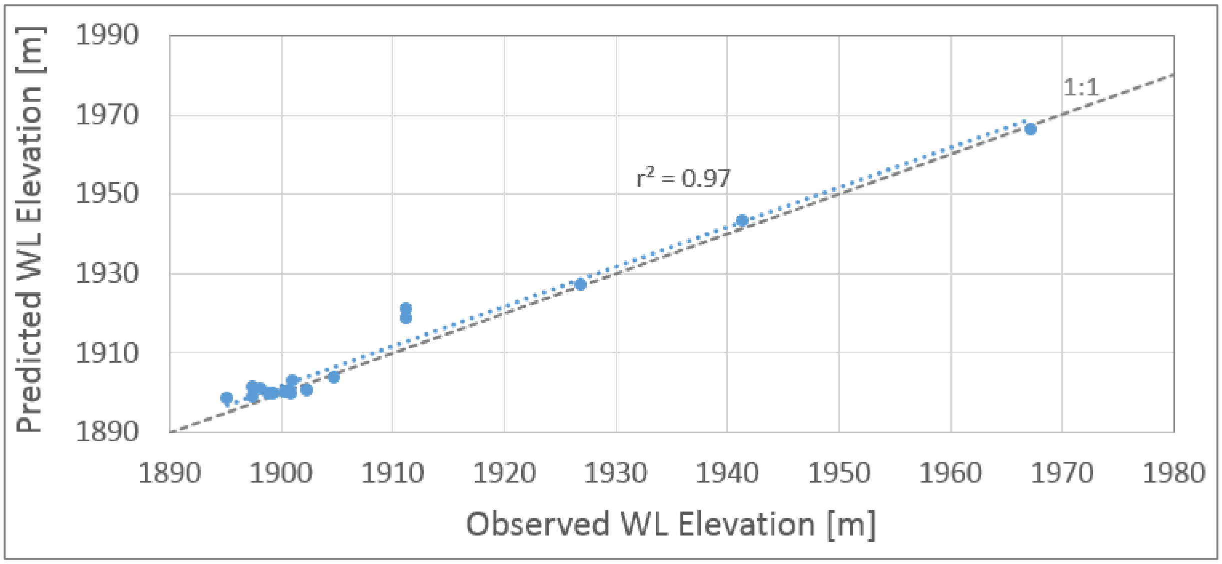

Figure 9: A comparison of observed and predicted steady state water levels for DWR wells.

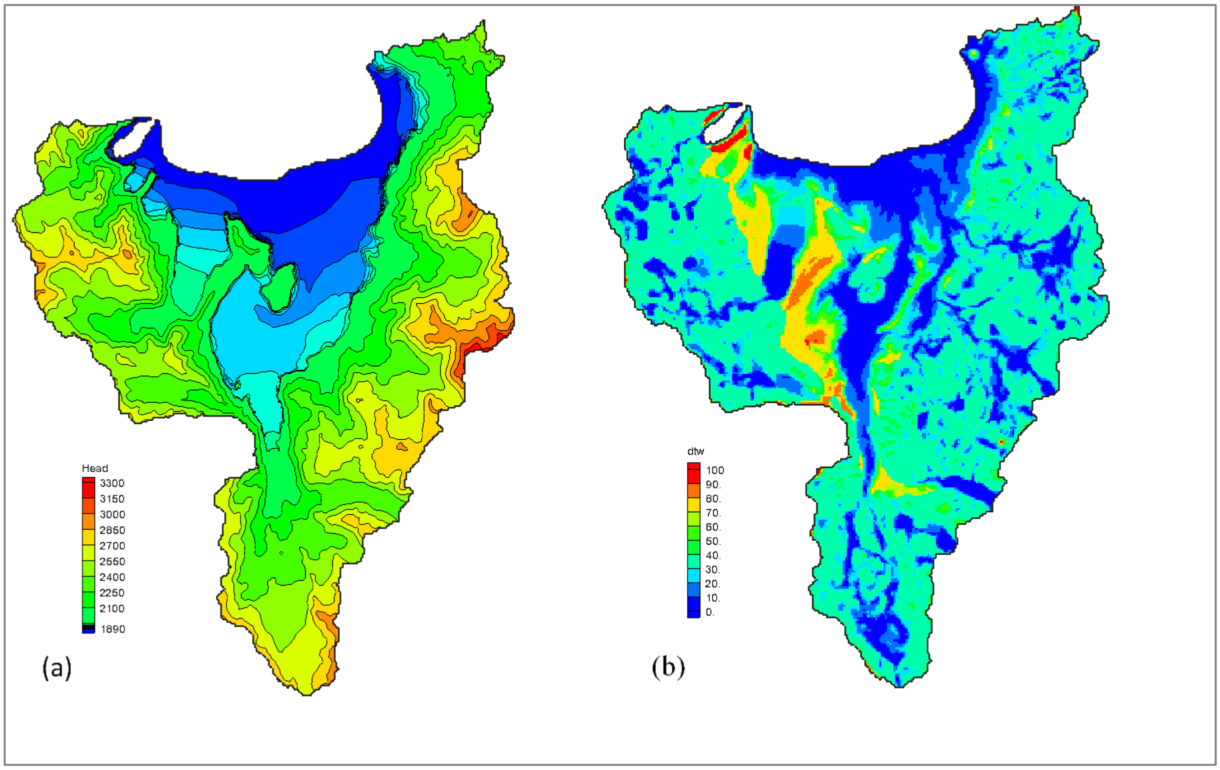

Figure 10: (a) Steady state water levels with 10 m contour intervals from 1890m -1950 m (blue), and 150 m contour intervals for >1950 m; and (b) DTW in meters.

Contours along river corridors and upland bedrock contain much steeper gradients spanning 1950 m to 3300 m (6398 ft to 10827 ft) and are largely controlled by topography. DTW are shallow (<10 m, < 32 ft) in regions of groundwater discharge such as the lower alluvial basin and along river courses where bedrock topography drives converging flow. Depths increase in upland portions of the model to approximately 100 m (328 ft).

4.2.4. Baseflow

Figure 11 compares estimated baseflow with the observed range. In general, the TVS groundwater model under estimates total flux to these gages by simulating only 84% observed mean. However, predicted baseflow falls within the observed range for most sites. The exception is gage 1033670 located in Zephyr Cove on Edgewood Creek in Nevada. Large precipitation events, including rain-on-snow events, can bias observed baseflow in November and December toward higher values than representative of truly groundwater derived discharge.

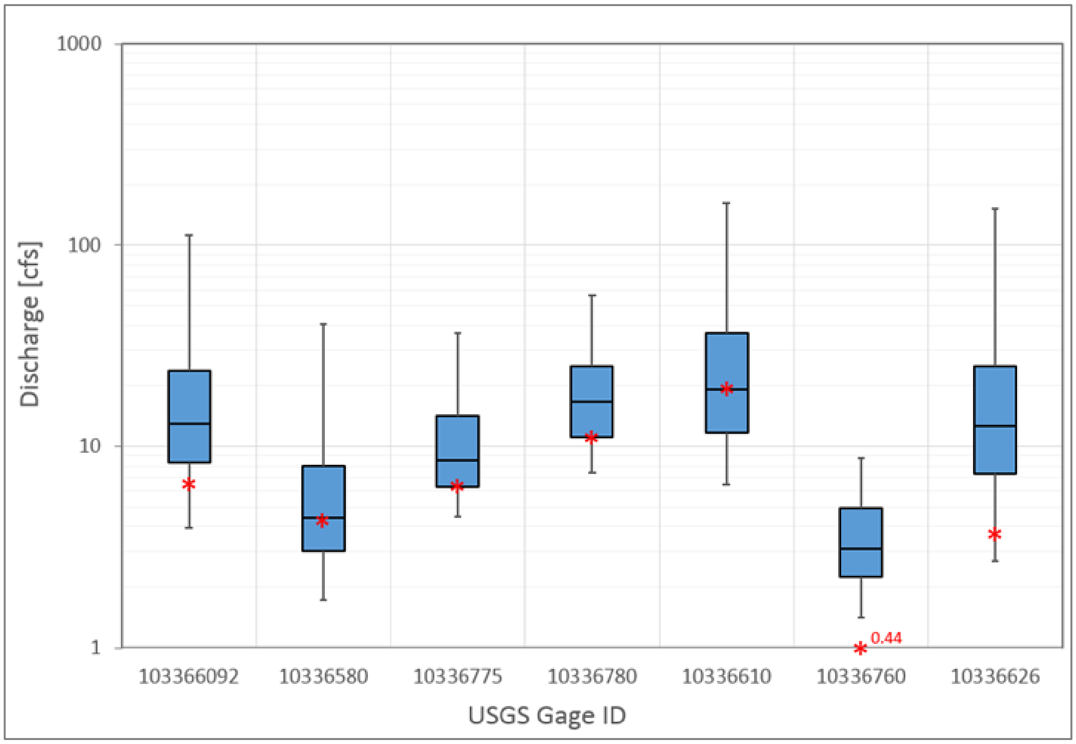

Figure 11: Comparison of predicted and observed baseflow for specified USGS gages.

4.2.5. Water Balance

All inflows to the TVS domain occur as recharge (42,280 AFY) with discharge to groundwater flux to Lake Tahoe matching the observed value (11,740 AFY) as determined as the USACE (2003), if one assumes average groundwater pumping between 1983 and 2014 is discharged to the Lake, by calibrating the GHB conductance term to 86.61 m^2/d/m (284 ft^2/d/ft). The remaining recharge is then exported through rivers as baseflow (30,540 AFY).

5. Transient Model

The transient model is run for water years 1983 through 2014 with no additional calibration performed. Specific yield is set to 0.1 for bedrock and 0.3 for alluvium while specific storage is assumed 1e-6 for all geologic units.

5.1. Transient Boundary Conditions

5.1.1. ET and Recharge

GSFLOW annually derived ET and recharge are provided in Figure 12. ET is not used directly in the TVS groundwater model, but plotted to show a comparison with recharge over time as a function of climate and water availability. ET and recharge are directly related and on average recharge is approximately 25% total ET. However, the relationship is not linear but is best described with an exponential function with recharge increasing faster than increases in ET.

Monthly recharge for a dry year (wy 1988) and a wet year (wy 2011) are shown in Figure 13 along with mean monthly recharge for the entire simulated time period in order to illustrate the temporal variability in recharge at the basin scale. On average, recharge peaks in May at 8,800 AF per month. During wy 1988, total annual recharge is only one-third average conditions at 13,400 AFY. Peak recharge is only 3,500 AF and occurs 1-2 months earlier than average conditions. In contrast, wy 2011is estimated to produce 79,500 AFY of recharge, or approximately two-times average conditions. Significant quantities of recharge occur throughout the fall and early winter, presumably with rain and early snowmelt with December recharge equaling 8,300 AF. A secondary peak in snowmelt derived recharge occurs in July producing nearly 15,000 AF per month. The spatial distribution of recharge at quarterly intervals (October, January, April and July) are provided in Figure 14. During wy 1988, recharge primarily occurs along the western and southern edges of the modeled domain, while the eastern mountains of the Carson Range experience much less precipitation. Subsequently, recharge is low in the Carson Range with recharge contributions primarily limited to its upper elevations during the early spring. Water year 2011 shows greater areal contributions in recharge across the entire domain with large contributions in recharge occurring from the Carson Range with lower elevations contributing more in the early spring (April) and higher elevations in mid-summer (July).

5.1.2. Groundwater Pumping

Groundwater pumping is done using the Multi-Node Well package (MNW2, Konikow et al. 2009) to allow for multiple screen intervals in a single borehole in which screen intervals span multiple layers and/or occupy only a fraction of a model layer. Forty-nine production wells (Figure 15) are simulated using pumping rates for 1983 through 2014. For screen depths refer to Figure 4. Annual pumping volumes are provided in Figure 16 with the maximum pumped volume occurring in 2007 at 9,716 AFY. The mean pumped volume is 7,759 AFY.

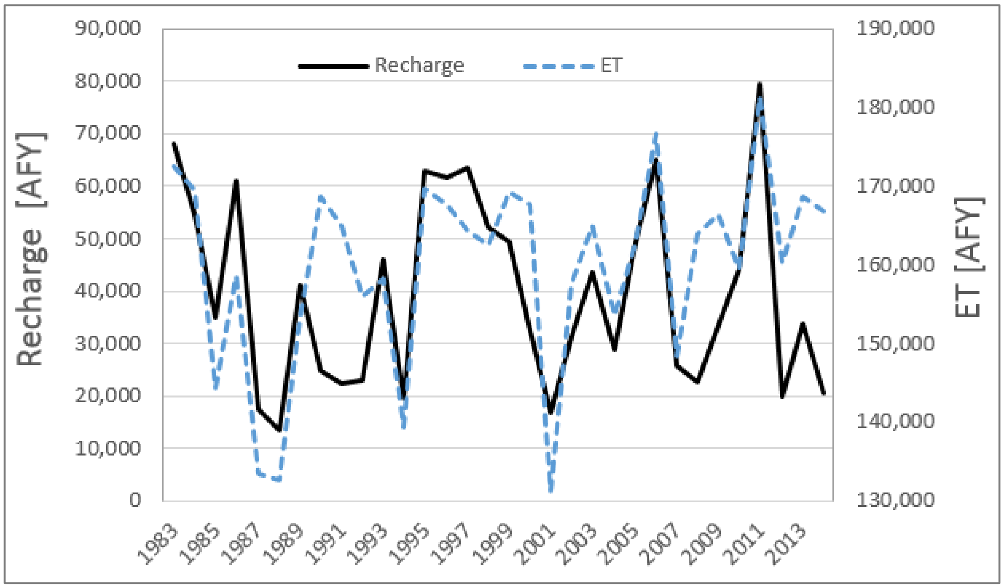

Figure 12: GSFRM simulated annual ET and recharge for water years 1983-2014.

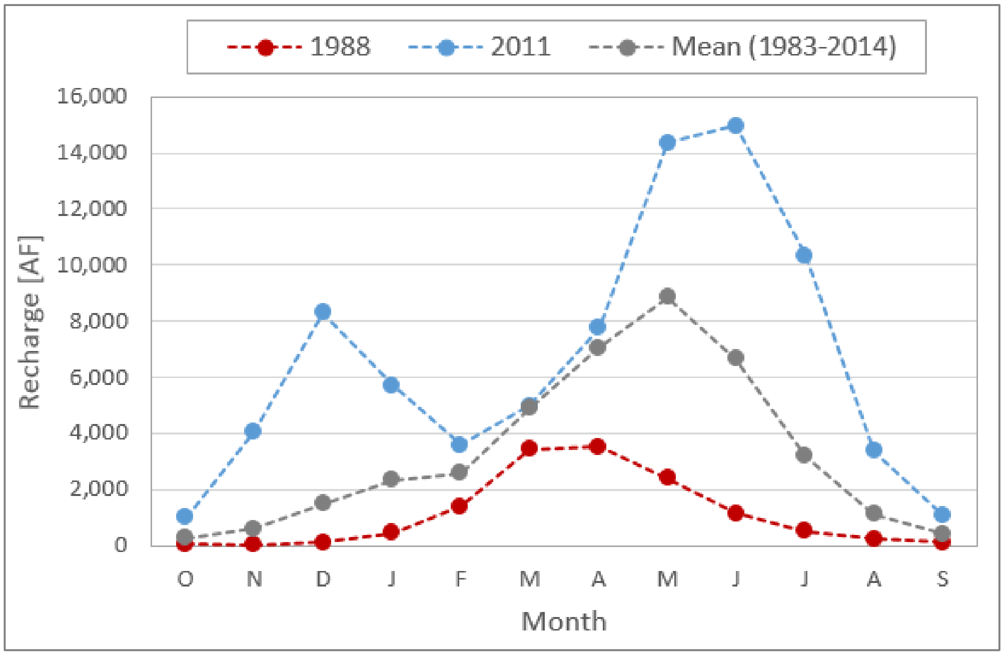

Figure 13: Basin-scale recharge for the driest water year during the simulation (1988) and the wettest year in the simulation (2011) with a comparison to mean monthly simulated recharge values.

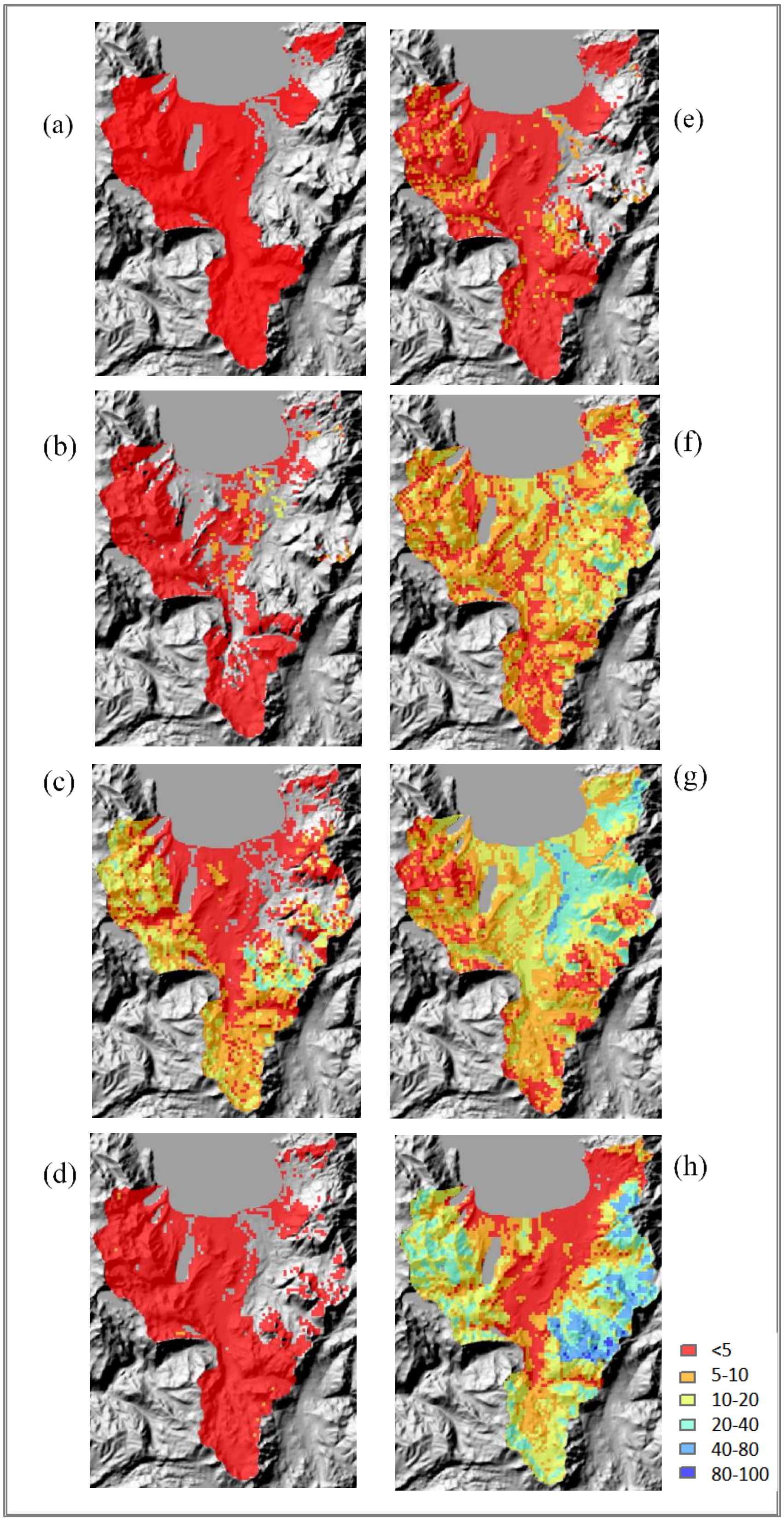

Figure 14: GSFRM derived spatial distributions of recharge (in/yr) across the TVS for a dry water year (a) October 1987, (b) January 1988, (c) April 1988 and (d) July 1988; and a wet water year (e) October 2010, (f) January 2011, (g) April 2011 and (h) July 2011.

Figure 15: Production well locations simulated with the TVS groundwater model.

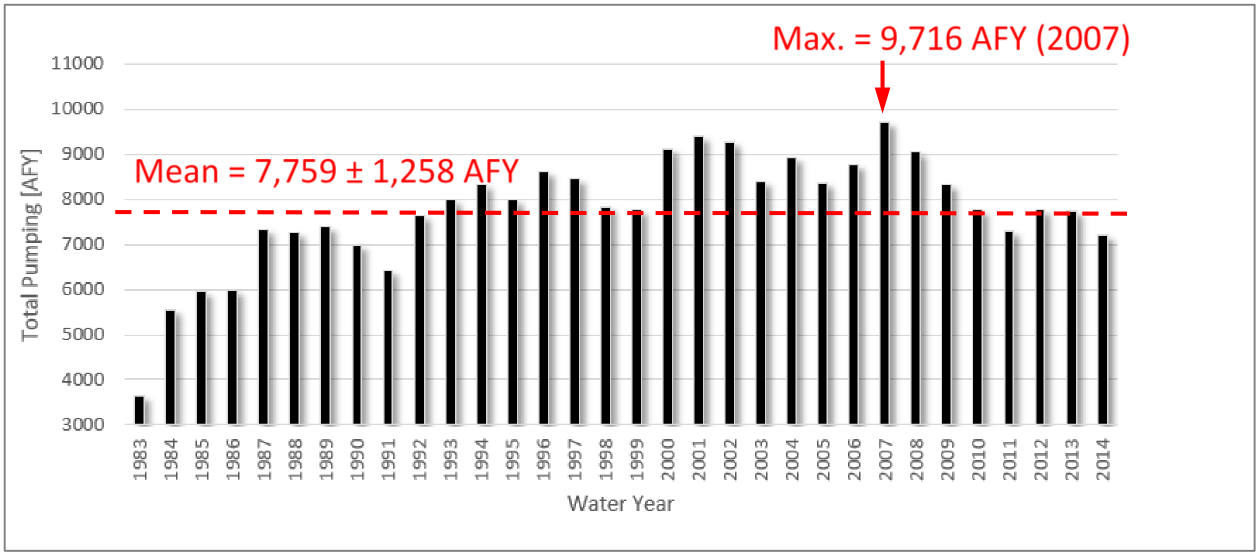

Figure 16: Annual pumping volumes simulated with the TVS groundwater model.

5.1.3. Lake Tahoe Stage

Monthly stage elevations for Lake Tahoe are input to the GHB package and are provided in Figure 17 with elevations ranging from 1897.20m (6224 ft) to 1899.9 m (6233 ft). Lake stage shows the influence of wet and dry periods with distinct declines occurring during droughts of 1987-1992, 2000-2004, 2007-2010 and 2012-2014. Rebound during wet years is rapid taking only a few years to rebound even from the most significant of simulated droughts.

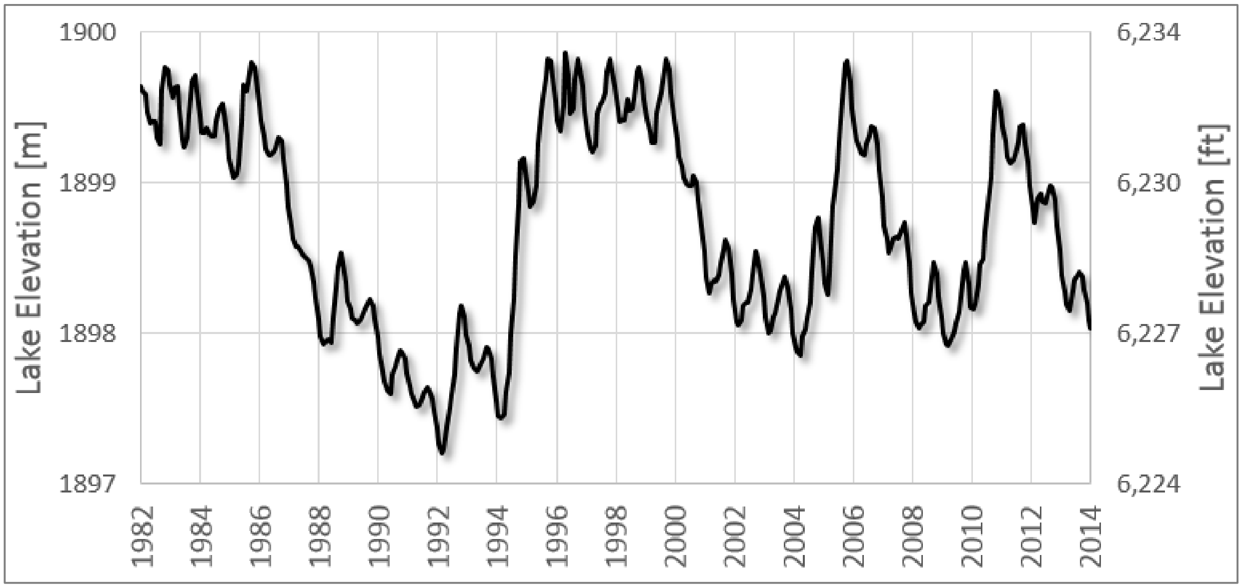

Figure 17: Lake Tahoe monthly observed stage used in the GHB package.

5.2. Transient Model Results

5.2.1. Water Levels

Depth of observations are assigned to the mean of screen interval for each well. If multiple screen intervals occur in a single borehole, then the observation depth was calculated as the length-weighted elevation. With no additional calibration, the transient TVS groundwater model predicts water levels with a mean residual equal to -3.2 m (2.6%), mean absolute residual of 6.6 m (5.3%) and a rmse of 11.2 m (9.0%). Error is less than 10% for all metrics considered and deemed acceptable. Figure 18 shows selected wells for comparison of predicted heads with observed data. Predictions follow trends in observation and in several cases align closely with actual observed data. Exceptions occur where large variability in pre-2000 data is evident (e.g. Sunset-Well, Mountain View Well). Some of these deviations may be related to pumping levels and not static levels. In addition, the model over predicts water levels by ~10 m in the central portion of the domain in the vicinity of the Bakersfield, Country-Club and Arrowhead wells.

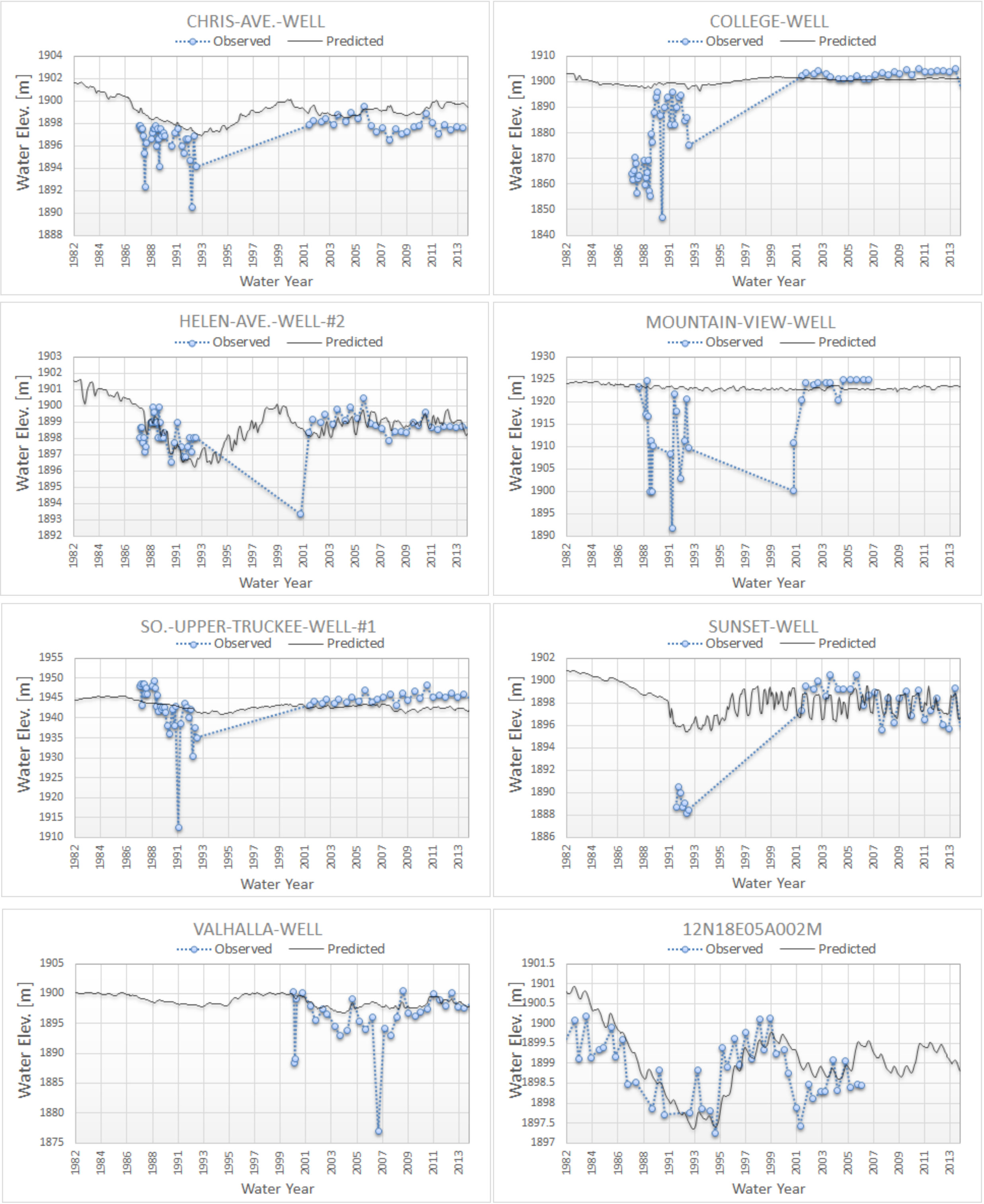

Figure 18: A comparison of predicted and observed water levels for select wells.

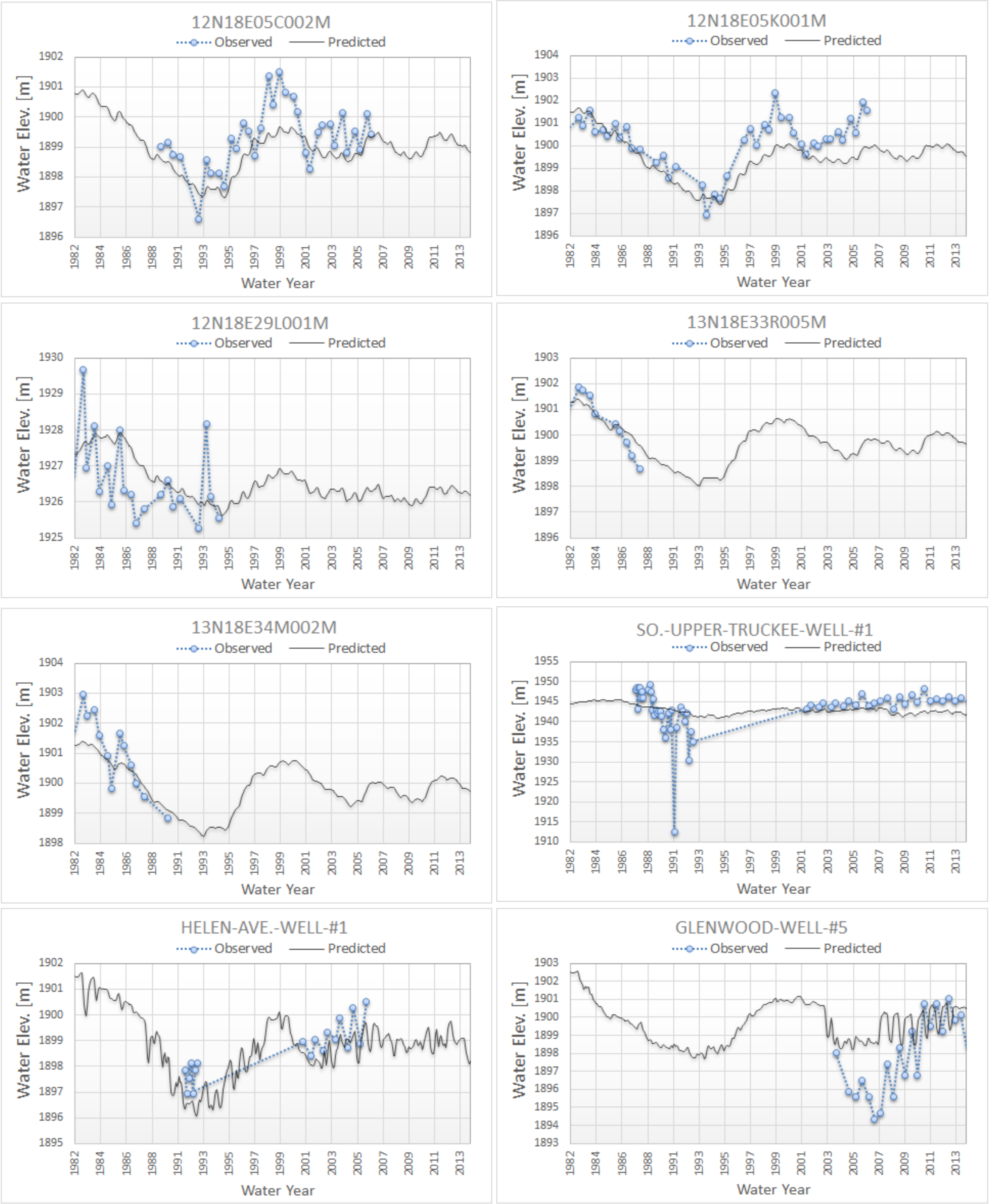

Figure 18 (continued): A comparison of predicted and observed water levels for select wells.

5.2.2. Water Budget

The simulated average water budget for wy 1983- 2014 is shown in Figure 19. Recharge is estimated to contribute 39,470 AFY. Baseflow to streams is the largest predicted loss of recharge at 28,430 AFY, groundwater pumping removes 7,770 AFY while groundwater flux to Lake Tahoe amounts to 5,240 AFY. Over the course of the simulation the average change in storage is positive at 1,980 AFY, with water tables declining slightly to balance the budget over the 31-year simulation period. Annual variability in components is provided in Figure 20. Baseflow appears to oscillate in response to recharge but the year-to-year correlation indicates a weak, negative correlation (r^2=0.06). A lag of 10-years induces a direct relationship to recharge but the correlation remains weak. TVS estimated groundwater flux to Lake Tahoe represents 13.3% of the water budget. This average groundwater flux is approximately 1.3-times the value presented by the USACE (2003) of 3,970 AFY but the simulated variability in flux (standard deviation = ± 3,060 AFY) captures the USACE estimated value. Groundwater flux to Lake Tahoe shows a modest direct relationship to recharge (r^2 = 0.17) and a significantly stronger indirect relationship to groundwater pumping (r^2 = 0.39). The largest predicted variability in the water budget occurs between recharge and changes in groundwater storage, with a strong indirect correlation between the two (Figure 21). A threshold emerges in the relationship between recharge and groundwater storage at approximately 41,400 AFY; below which groundwater storage is positive (water table elevations drop), and above which storage becomes negative (water table elevations rise).

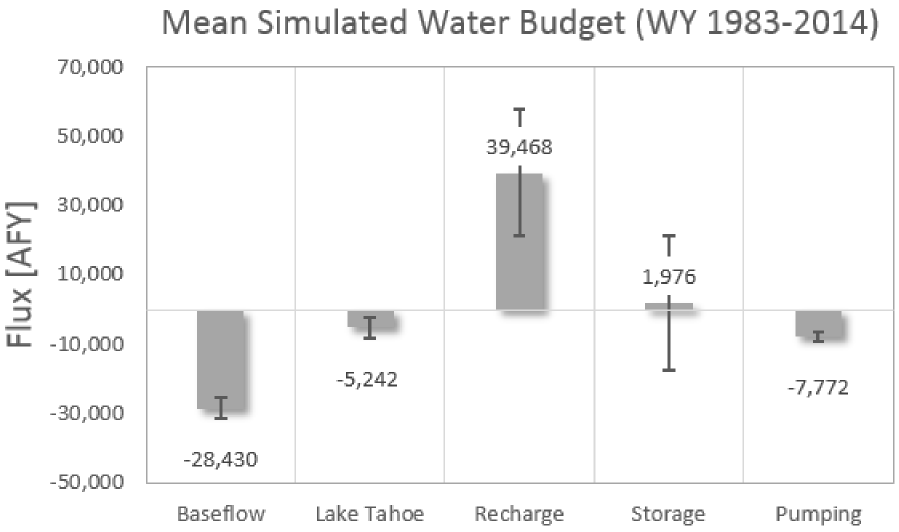

Figure 19: Mean simulated water budget (water years 1983-2014).

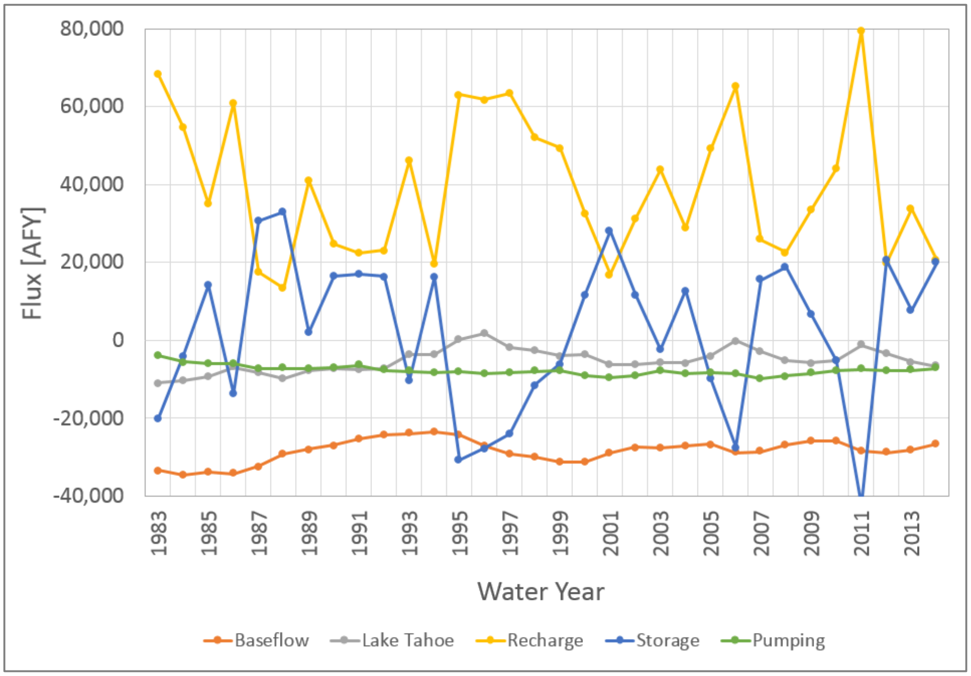

Figure 20: Annual water budget components from water year 1983 to 2014.

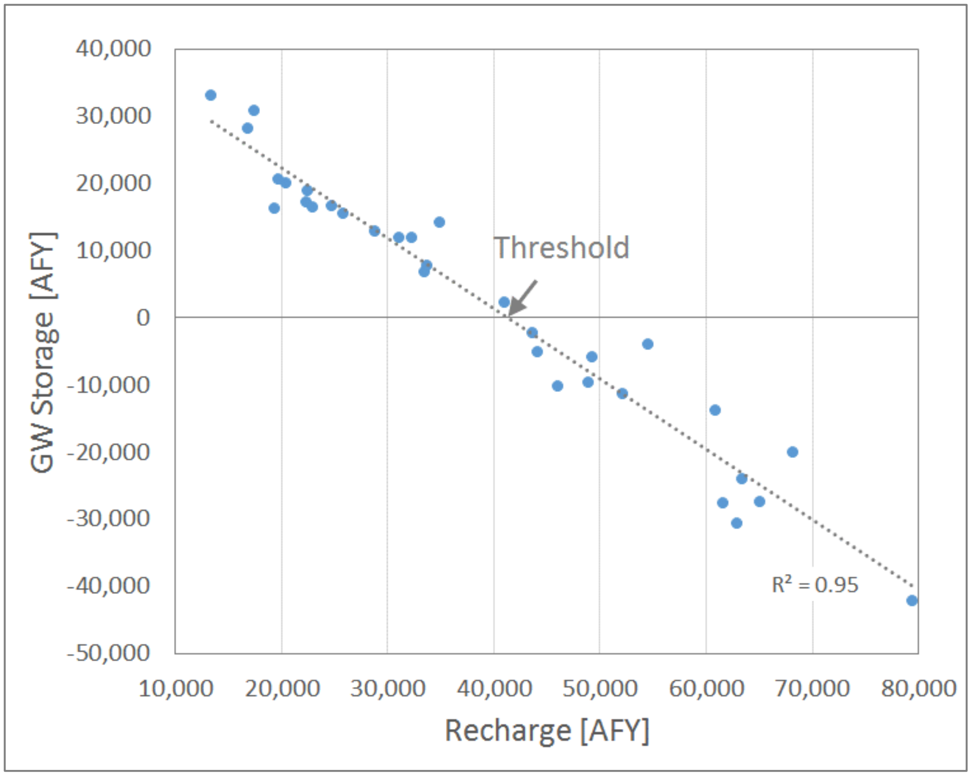

Figure 21: Correlation between recharge and changes in ground water storage with a threshold of approximately 41,400 AFY in recharge identified.

6. Model Limitations

The TVS groundwater model is able to capture hydrologic trends based on reducing complex geology and boundary condition forcing into its numeric platform for numeric efficiency. In simplifying geologic complexity, however, the model produces too shallow a gradient in the lower elevation regions of the model, while higher elevation wells show a variable response of being over or under predicted to indicate an inability to properly characterize site heterogeneity with respect to either hydraulic properties or climate-induced recharge. However, overall error is less than 10% and considered appropriate for the purposes of this model. The TVS model incorporates the standard assumptions of the groundwater flow equation in which flow is considered laminar and inertial forces, velocity heads, temperature gradients, osmotic gradients and chemical concentration gradients are not considered. It is also noted that the water budget is driven by recharge calculated from the GSFRM. This physically based model provides spatial and temporal distribution of recharge based on complex interactions of climate, land use and geology to provide strength to the TVS. The TVS model acquires the assumptions inherent in the construction of the GSFRM. Specifically, all recharge is calculated at the 300 m resolution using soil, vegetation and geologic information averaged over this scale. Recharge from the soil zone moving to the groundwater system decreases when the water table rises into the soil zone. If the water table is at or above the soil-zone base, evapotranspiration loss from groundwater occurs at the net potential ET rate. Also, the unsaturated zone flow (UZF) package that simulates recharge solves a vertical one-dimensional form of Richards' equation. This assumption mostly affects evapotranspiration and not recharge, but since recharge is a part of the overall water budget, it could have an impact. No studies have been conducted to test what impact it may have on modeled output.

7. Conclusions

The model captures general watershed hydrology at a relatively fine resolution (100 m) over a large domain (404 km^2). Water balance estimates at monthly timescale are conducted over a 30+ year period by incorporating a simplified version of the complex geologic information from the STPUD with recharge calculations based off of the GSFRM that accounts for complex feedbacks in the energy-water balance for the region. The TVS groundwater model, thereby includes a level of detail in boundary conditions not typically available to MODFLOW at the scale of the TVS. Recharge is considered the sole input to the basin and is divided primarily to stream baseflow and to a lesser extent to groundwater pumping and groundwater flux to Lake Tahoe. Overall, the 30+ year period shows a slight decline in water levels with groundwater storage adding to the water budget. However, at the annual scale, large fluctuations in groundwater storage are indirectly related to recharge. The TVS basin is found to operate on a threshold response to recharge in which groundwater levels decline when recharge is less than or equal to approximately 40,000 AFY and to rebound when recharge is larger. Flux to Lake Tahoe is only modestly related to recharge. Instead, it is more strongly correlated indirectly to groundwater pumping.

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