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Technical Memorandum

UVRGA Groundwater Model Sensitivity Analysis and Calibration Update

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Executive Summary

The depletion of interconnected surface water (ISW) sustainability indicator is a key component of the Upper Ventura River Groundwater Agency (UVRGA) Groundwater Sustainability Plan (GSP). The GSP identifies the potential for significant and unreasonable effects on steelhead when surface water flows decline below 2 cubic feet per second (cfs), as measured at the Foster Park United States Geological Survey (USGS) gage 11118500 located at the Camino Cielo bridge. Therefore, the GSP includes sustainable management criteria (SMC) intended to prevent streamflow from declining below 2 cfs at Foster Park as a direct result of groundwater extraction and to avoid further depletion of streamflow from groundwater extraction when streamflow is below 2 cfs. As GSP implementation is guided by numerical modeling, it is important to ensure UVRGA's numerical model can accurately simulate the lower range of Ventura River flows approaching the 2 cfs threshold. This memorandum describes work INTERA undertook to improve the UVRGA numerical model's ability to simulate low flows in the Ventura River relevant to GSP implementation and to improve delineation of the model's limitations in this regard.

The UVRGA numerical groundwater model simulates groundwater/surface water interactions and is used to estimate the depletion of ISW due to groundwater pumping near the Upper Ventura River. The Upper Ventura River is a dynamic, high-energy system that changes both spatially and temporally. Perennially wet and dry reaches of the river are highly dependent on groundwater/surface water interactions driven primarily by available groundwater in storage and alluvial thickness. In addition, storm events can change the river channel geomorphology and riparian vegetation. The model relies on gaged streamflow data to represent the surface water conditions of the Ventura River accurately; therefore, understanding what components of the modeled streamflow are most sensitive to changes to inputs is a key process to maintaining and calibrating a well-built model. INTERA, with input and review by UVRGA's Executive Director Bryan Bondy, has completed the tasks summarized in **Table ES-1** to improve the model's ability to represent streamflow conditions and evaluate model use limitations.

Table ES-1. Summary of work completed and insights gained.

Work Completed	Insights Gained	Section Discussed
River Channel Change Evaluation: Evaluated impacts of changes in river channel geomorphology from January 2023 flooding event on model	Modeled streamflow results are generally insensitive to changes in streambed elevation and location of channel. Future updates to channel geomorphology following extreme flood events appear not to be critical for model performance.	2.1
Model Verification: Checked model performance using data post-calibration data (i.e., data after 2018)	Model found to overpredict low streamflows during post-calibration period (i.e., after 2018). Additional model calibration determined to be warranted.	2.1
Critical Review of Streamflow Data: Quantified errors in	Uncertainty in streamflow data is significant and impacted prior model	2.2

Work Completed	Insights Gained	Section Discussed
streamflow datasets used for model inputs and calibration	calibration. Removed unreliable data and accounted for streamflow measurement attributes (i.e., measurement quality ratings, measurement location). Developed upper and lower estimates of surface water inflows to basin to bracket model uncertainty and switched streamflow calibration dataset at USGS gage to error-barred, location-based measurements instead of rating curve.	
Update Other Model Inputs Using New Data	Updated model with data obtained since model construction: previously unavailable well logs (basin thickness), groundwater levels collected by UVRGA, and pumping rates from UVRGA well registration and groundwater extraction reporting program.	2.3
Sensitivity Analysis: Assessed sensitivity of model calibration to changes in key model parameters.	Determined key model parameters in different hydrogeologic zones that could improve model calibration and predictive ability.	3.2
Model Calibration Update: Updated the model calibration to improve its fit to observed streamflow data.	The model's ability to represent streamflow (especially low flows) improved significantly.	4.1
Review of Model Uncertainty: Assessed uncertainty in streamflow inputs for the model.	A high range in modeled streamflows was produced, which informed the recommendation for a predictive uncertainty analysis of the model.	4.1.2

The investigation of the streamflow measurement data refined the model representation of streamflow and provided direction for a focused calibration update of the model. The updated model is significantly improved in comparison with the original model developed for the GSP. The model can now more accurately represent Ventura River streamflow under low-flow conditions, which is critical for the GSP implementation. However, the predictive uncertainty of simulated streamflow requires further investigation to quantify depleted streamflow optimally and assess undesirable results for the Basin. This technical memorandum provides additional detail for each of the completed tasks and associated lessons learned shown in the table above.

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Acronyms and Abbreviations

cfs	cubic feet per second
GSP	Groundwater Sustainability Plan
HK	horizontal hydraulic conductivity
INTERA	INTERA Incorporated
ISW	interconnected surface water
KGE	Kling–Gupta Efficiency
LiDAR	Light Detection and Ranging
MAE	Mean Absolute Error
NSE	Nash–Sutcliffe Efficiency
RMSE	Root Mean Square Error
RSS	Residual Sum of Squares
SFR-K	streambed hydraulic conductance
Ss	specific storage (model layer 2 only)
Sy	specific yield
TM	technical memorandum
USGS	United States Geological Survey
UVRGA	Upper Ventura River Groundwater Agency
UVRGB	Upper Ventura River Groundwater Basin
VK	vertical hydraulic conductivity

1.0 Introduction

INTERA Incorporated (INTERA), with input and review by the UVRGA Executive Director, Bryan Bondy, developed a numerical groundwater model (model) of the Upper Ventura River Groundwater Basin (UVRGB, or Basin) in support of the Groundwater Sustainability Plan (GSP) (UVRGA, 2022a) for the Upper Ventura River Groundwater Agency (UVRGA). The model is an important tool for GSP implementation, with a primary purpose to estimate depletion of interconnected surface water (ISW) within the Basin.

The details behind the original model build, calibration methodology, and predictive results used for the GSP are documented in Appendix H of the GSP (INTERA and Bondy, 2022). The original model was calibrated to streamflow and groundwater level data for the 2005-2018 period, and the model has been extended incrementally for each GSP Annual Report through water year 2023 without additional calibration (UVRGA, 2022b; 2023; 2024). The model was not extended for the water year 2024 annual report (UVRGA, 2025) because the model was “out-of-service” for this calibration update project.

This technical memorandum (TM) summarizes the work performed to update the model calibration and is organized into five sections:

1. **Introduction**
2. **Background** – a summary of all the relevant information related to the model calibration update.
3. **Sensitivity Analysis and Setup for Calibration Update** – statement of calibration goals, sensitivity analyses, updates to calibration datasets, and calibration setup.
4. **Calibration Results** – description of calibration results and uncertainty analysis.
5. **Conclusions and Limitations** – key findings of the model calibration described in this TM and a discussion of the model limitations.

2.0 Background

A general timeline of the UVRGA model development, along with key steps leading to the updated and recalibrated model, are shown on **Figure 2-1** and described in this section.

The original model calibration dataset covered the 2005-2018 period, and the latest version of the model—prior to the work completed for this TM—extended during annual report preparation up to and including water year 2023 (UVRGA, 2024).

2.1 Review of Work Completed Following the January 2023 Flood

A major flood event on January 10, 2023, changed the Upper Ventura River channel geomorphology. Following this, the model was updated to reflect the post-flood channel morphology, and the updated model output was reviewed to assess the impact of channel morphology changes on model results (INTERA and Bondy, 2024). A Light Detection and Ranging (LiDAR) survey was completed by UVRGA in 2023 to provide updated channel elevation data, which was then input into the model This work showed that model results are generally insensitive to changes in streambed elevation and location of channel and that future updates to channel geomorphology following extreme flood events do not appear to be critical for model performance.

This work also provided an opportunity to review the post-calibration period (i.e., post-2018 model performance). This is referred to a "model verification" in the modeling community. The model verification revealed that the calibration of model-simulated streamflow during the post-calibration period (i.e., post-2018) was significantly poorer than during the calibration period (i.e., error between simulated and observed streamflow of <10 cubic feet per second [cfs] averaged 4.4 cfs, as compared to an error 1.2 cfs of for the pre-2018 dataset). The model error during the verification period exceeded the 2 cfs minimum threshold included in the GSP, indicating the need for an investigation into potential sources of error related to streamflow data, model sensitivity analysis, and model calibration update (INTERA and Bondy, 2024).

2.2 Critical Review of Streamflow Data

Ventura County maintains streamflow gages on both Matilija Creek forks (604 and 602B) and San Antonio Creek (605A), and the United States Geological Survey (USGS) maintains a streamflow gage on the Ventura River at Foster Park (Station ID 11118500) (**Figure 2-2**). Streamflow data are incorporated into the model in two ways: (1) gaged tributary inflows from the Matilija and San Antonio Creeks serve as a model input for the simulated Ventura River streamflow, and (2) gaged streamflow at the USGS Foster Park gage on the Ventura River (11118500) is used to calibrate the model simulated Ventura River streamflow (Figure 2-2). Note the "streamflow calibration dataset" referenced throughout this TM represents the Foster Park USGS 11118500 gage data.

In general, stream gage operation consists of continuous stage monitoring using a river level sensor combined with periodic manual flow measurements. The continous stage values are converted to streamflow using rating curves, which are developed using a stage-discharge relationship and adjustments (a.k.a. "rating curve shifts") to account for changes in the stage-discharge relationship over time. Available continuous and manual streamflow data were compiled and checked for any visible anomalies, shifts, or drifts.

Initial findings were shared with USGS and Ventura County staff responsible for field measurements and data processing, and multiple discussions took place to improve understanding of gaging methodology. Guidance and feedback from the County and USGS provided detailed information to interpret streamflow measurement data and calculate the ranges of measurement error and uncertainty in rating curve estimation (INTERA, 2024). The key findings of the streamflow data evaluation included (1) identification of errors in streamflow inputs to the model, (2) ranges of error for manual measurements, (3) uncertainty assessment of streamflow rating curves, (4) refinement of streamflow calibration datasets, and (5) insight to guide sensitivity analysis and calibration updates to improve the model's ability to match streamflow data. **Figure 2-3** shows an example hydrograph for the Foster Park gage and the range in measurement error. These findings were documented in a TM submitted to UVRGA in 2024 (INTERA, 2024).

The model's streamflow calibration dataset was updated based on the findings of the critical review of streamflow data. The updates included ranges of errors on streamflow measurements, an emphasis on baseflow (i.e., sustained low flows following storm events) manual measurement data, and removal of the rating curve estimated data from the quantification of calibration statistics. The rating curve for the Foster Park gage is updated frequently following manual streamflow measurements, and the reporting on these updates was unavailable for review; therefore, the uncertainty associated with streamflow estimated from the rating curve was considered unreliable for use as a calibration dataset. The rating curve estimates of streamflow data can still be used for a visual and qualitative assessment of the match between simulated and observed streamflow; however, these estimates were not used in this calibration. The model is not expected to match the rating curve estimated data because it is mostly based on data collected at locations other than the Foster Park gage location. Further refinement of the streamflow calibration dataset took place during the model calibration update, which is described in Section 3.3.

2.3 Other Model Updates

The model was also updated using new data and further review of existing data. These model updates included:

1. Converting model stress periods from a mix of daily and monthly fully to daily periods to reduce estimation error associated with averaging flows over month-long periods;
2. Incorporating data from the UVRGA well registration and groundwater extraction reporting program;
3. Updating the Ventura River-Coyote Creek confluence location and associated Ventura River channel characteristics;
4. Updating the modeled bedrock surface in selected areas based on previously unavailable boring logs; and
5. Adjusting model run-time efficiency.

These updates were completed prior to the calibration update work. Additional details on the above listed model updates are provided in the following subsections.

2.3.1 Model Stress Periods

A stress period for the model is a time interval where model inputs, such as pumping, streamflow, or recharge, are held constant. The model stress periods were originally designed to be monthly; however, they were subdivided into daily for the wet season (November-March) and monthly for the dry season (April-October) to reduce model computational time and output file sizes. Conversion to global daily stress periods was implemented to improve the accuracy of modeled low streamflow and represent effects of groundwater extraction on streamflow during the dry season.

2.3.2 Updates to Modeled Pumping Rates

The estimated pumping rates for individual wells within the Basin were refined based on data from UVRGA's well registration and groundwater extraction reporting program. This program has collected information from the well owners about well status (active, backup, abandoned, destroyed) and groundwater extraction quantities. Wells with estimated extractions exceeding 2 acre-feet per year are required to install a flowmeter and report groundwater extractions on a quarterly basis. The well registration responses and groundwater extraction reporting data were used to update the simulated pumping rates within the model to represent groundwater extractions more accurately.

2.3.3 Coyote Creek Confluence Model Setup

Information provided by USGS on the location of the Foster Park gaging station and subsequent inspection of the Upper Ventura active channel braids in the Foster Park area indicated the original model setup inaccurately represented the Coyote Creek confluence with the Ventura River. Two channels for the Ventura River are regularly noted at the Foster Park gage in the USGS manual measurement notes. The original model had one channel for the Ventura River and one channel for the Coyote Creek at the Foster Park gage location, with the Coyote Creek confluence occurring downstream of the Foster Park gage. However, based on communication with USGS staff and additional inspection of aerial photography, the Coyote Creek confluence was determined to be upstream of the Foster Park gage, and two channels represented the Ventura River at the Foster Park gage (**Figure 2-4**). This updated the calculation of modeled streamflow at the Foster Park gage to be the sum of the streamflow at both channels.

2.3.4 Updates to the Modeled Bedrock Surface

Previously unavailable boring logs provided new data to update the depth to bedrock for the model. Twelve locations were added to the bedrock interpolation, and the bedrock surface was either raised or deepened (**Figure 2-5**). In general, the bedrock surface was raised in the vicinity of the data near Santa Ana Boulevard and deepened in the south near Casitas Springs.

2.3.5 Model Run Time Improvements

Longer model run times were encountered after converting all stress periods to daily (Section 2.3.1) and incorporating the other model updates discussed in the previous subsections. Adjustments to the model solver maximum iterations were tested to optimize the run time while preserving the model simulation accuracy. Model run times were generally shortened by 50%, which improved the efficiency of running several model realizations for the sensitivity analysis and calibration update.

2.4 Summary of Model Background

The model development timeline (Figure 2-1) shows tasks completed for the model prior to calibration update and highlights the key steps which led to the updated model. In summary, the following key findings are noted:

1. Changes to the Ventura River channel geomorphology had no significant impact on the model performance.
2. Verification of the post-calibration streamflow data (i.e., post-2018) indicated the model required evaluation of potential sources of error in the streamflow data and calibration update.

3. Updates to the model streamflow calibration update dataset were made based on critical review of the streamflow data and consultation with USGS. A scope for sensitivity analysis and calibration update was prepared at this point.
4. Model updates were made based on updated data and increased the temporal resolution of the model prior to sensitivity analysis and calibration update.

The setup for sensitivity analysis and calibration update is described in Section 3.

3.0 Sensitivity Analysis and Setup for Calibration Update

This section presents the sensitivity analysis and calibration update of the original model. A sensitivity analysis (Section 3.2) was performed (1) to determine which model parameter inputs have the most effect on simulated streamflow at the Foster Park gage and (2) to help streamline the calibration of the model by eliminating insensitive parameters and constraining the range of parameter values for calibration. The calibration update of the model was then performed to identify the best combination of parameter changes needed to achieve the calibration goals (Sections 3.3 and 3.4).

3.1 Calibration Goal and Overall Approach

The overarching goal of the calibration update was to improve the model's ability to match observed streamflow at the USGS Foster Park gage while maintaining a similar level of calibration to observed groundwater levels to the original model. Important factors for the streamflow calibration dataset include:

- A primary focus on matching streamflow during baseflow recession and low-flow conditions (i.e., <10 cfs) at the Foster Park gage location.
- An emphasis on post-2018 streamflow data, due to the (1) results of the model verification, which indicated the calibration during this period was significantly poorer than during the original calibration period (Section 2.1), and (2) Foster Park manual streamflow measurements were more reliable after 2018 (i.e., measurement locations were either unknown or downstream of the basin where the model lacks available data).
- Removing the rating curve estimated streamflow and using only manual measurement data for the observed dataset used in calibration (see Section 2.2).
- Accounting for the manual measurement distance from the gage (see Sections 3.3.1 and 3.3.2).
  - Due to manual measurement location issues (see Section 3.3.1), pre-2017 streamflow data were largely unreliable because the streamflow measurement locations were either unknown or made downstream of the basin where the model lacks data. These data were not used when quantifying the closeness of fit between simulated and observed streamflow.
- Updated groundwater level observations were also included in the calibration process to ensure the model maintained an accurate representation of observed groundwater conditions.

These factors are important because the model is used to estimate streamflow depletion, and minimum thresholds for the depletion of ISW can be exceeded during low flows when depleted streamflow is <2 cfs. The accuracy of streamflow measurement data used for calibration is critical for assessing the model's performance.

3.1.1 Calibration Approach Using PEST++IES

The model computation time varies from approximately four to eight hours depending on the processor. Calibrating the model through manual trial-and-error was computationally infeasible, given the run times and the number of runs required to explore the parameter space. To address this, the calibration update utilized the automated calibration software suite Parameter Estimation Iterative Ensemble Smoother (PEST++IES; White, 2018), which provides an efficient, objective framework for numerical model calibration.

PEST++IES offers several advantages over manual calibration. It automates the adjustment of parameter ensembles (combinations of multiple parameter values and spatial distribution) within prescribed zonal (geographic) ranges and iteratively minimizes differences between simulated and observed data at specified targets using a quantitative objective function representing the fit between model simulated results and field measurements. In addition, the use of pilot points, rather than zones of constant parameter values, allows a flexible spatial variability in parameters. Pilot points are discrete locations where parameter values are perturbed and provide a smooth interpolation of parameters over the model grid between pilot points. The ensemble-based approach improves efficiency in exploring parameter space, requiring fewer model runs versus testing each parameter individually.

3.2 Sensitivity Analysis

Following the incorporation of updates described in Section 2.3, INTERA conducted a series of sensitivity runs to identify which parameters most influenced simulated streamflow at Foster Park and to guide selection and setup of parameters to include in the calibration. The model parameters tested for sensitivity included horizontal and vertical hydraulic conductivity (HK and VK, respectively), specific yield (Sy), specific storage (Ss; model layer 2 only), and streambed hydraulic conductance (SFR-K). Parameter adjustments focused on the Casitas Springs, Santa Ana, and Robles hydrogeologic zones (**Figure 3-1**). INTERA completed and analyzed a total of 60 model runs for sensitivity based on the combinations of parameter adjustments for each hydrogeologic zone.

Reducing Sy in the Casitas and Santa Ana zones—and therefore unconfined groundwater storage upstream of Foster Park—lowered baseflows and steepened the recession portion of the streamflow curve. **Figures 3-2** and **3-3** show the simulated streamflow response at Foster Park due to changes to Sy in the Santa Ana and Casitas Springs zones, respectively. Sustaining baseflow at the Foster Park gage is generally controlled by the amount of groundwater storage directly upstream; therefore, changes to Sy in the Robles and Mira Monte had little effect because of their greater distance from the gage. Similar effects were observed for adjustments to the Ss in layer 2.

Simulated streamflow at the Foster Park gage was also sensitive to adjustments to HK in the Casitas Springs and Santa Ana zones. Increasing HK in the Casitas Springs zone reduced baseflows and steepened recessions, and decreasing HK led to generally higher baseflows (**Figure 3-4**). Increasing HK in the Casitas Springs zone increased the rate of groundwater flow during wet periods, leaving less water to support streamflow later in the season, and vice versa. Reducing HK in the Santa Ana zone decreased simulated streamflow at Foster Park, while raising HK increased it, which had the opposite effect as adjustments to HK in the Casitas zone (**Figure 3-5**). Because the Santa Ana zone is upgradient of the Casitas zone, lowering HK reduced the rate of groundwater flow, which restricted the groundwater discharge to streamflow farther downstream in the Foster Park gage area. Conversely, increasing HK in the Santa Ana zone facilitated faster transmission of groundwater toward the Foster Park gage, which sustained higher flows during the dry season.

Additional sensitivity runs were performed with the Casitas Springs zone subdivided into upstream and local areas near Foster Park (**Figure 3-6**). Approximately half of the basin groundwater extraction occurs near the Foster Park gage, and this additional zone isolated the model parameters in the vicinity of the pumping wells to explore the effect of changes to HK upstream of the pumping center. These runs showed that simulated streamflow was most sensitive to HK changes immediately around Foster Park, while similar changes farther upstream had smaller effects. **Figure 3-7** shows the HK increased by a factor of 1.5 for both the upper and lower Casitas Spring zones.

Streamflow at Foster Park was largely insensitive to changes to VK in all zones and to changes in SFR-K in the Casitas and Santa Ana zones. Changes to SFR-K in the Robles zone produced a stronger response to simulated streamflow at Foster Park. However, increasing SFR-K in the Robles zone led to the simulated channel going dry in many of the streambed reaches in the Robles zone, which was inconsistent with independent wet/dry surveys conducted by UVRGA (2022a); therefore, these adjustments were excluded from the calibration setup.

In summary, the manual sensitivity analysis identified Sy and HK in the Santa Ana and Casitas zones as the parameters exerting the most influence on simulated streamflows at Foster Park. With the Casitas zone subdivided, HK adjustments in the lowermost zone near the gage affected streamflow the most. Reduction in storage parameters in the upstream portions of the Casitas zone and the Santa Ana zone led to noticeable decreases in simulated baseflow. These findings guided the selection and prioritization of parameter groups, definition of parameter bounds, and setup of the PEST++ IES framework.

3.3 Updates to Calibration Datasets

This subsection describes the updates to the streamflow and groundwater level calibration datasets for the model calibration update. For the original model calibration, the rating curve estimated streamflow was qualitatively used to evaluate the closeness of fit between simulated and observed data. Through the critical review of available streamflow data and additional analysis of modeled streamflow output during sensitivity analysis, the streamflow dataset was updated to focus on a quantifiable comparison of simulated and observed values. This focused on manual streamflow measurements with consideration of measurement error and location. In addition to modifications to the streamflow calibration dataset, the groundwater level calibration dataset was expanded to include post-2018 measurements.

3.3.1 Streamflow Measurement Distance Analysis

The Foster Park gage (11118500; see Section 2.2) manual streamflow measurements were collected by USGS field staff measuring flow across a cross-sectional area of the Ventura River channel. Accessibility to the channel near the gage can be limited due to riparian vegetation; therefore, field staff frequently take manual flow measurements at a distance from the actual location of the Foster Park gage. The recorded distance from the Foster Park gage where streamflow measurements have been taken ranged from more than 800 feet downstream to about 620 feet upstream. The variability in streamflow measurement location introduces uncertainty that went unrecognized and unaddressed during calibration of the original model, which compared simulated streamflows to the rating curve-estimated streamflows reported for the Foster Park gage. Due to the inconsistency in manual streamflow measurement location used to develop the rating curve, the rating curve stage-discharge relationship is not representative of the actual gage location (i.e., 11118500), and streamflow estimated using the rating curve is therefore unreliable and not used for the calibration update.

The Foster Park gage is located in a highly dynamic reach of the Ventura River, with a subsurface dam approximately 1,000 feet upstream of the gage and a prominent bedrock uplift (reduced aquifer thickness) immediately downstream of the gage. **Figure 3-8** presents a cross section of the model grid in the vicinity of the Foster Park gage and shows the variable depth to bedrock and relative location of the gage and subsurface dam. Together, these features create steep hydraulic gradients and large changes in stream-aquifer exchange over short distances. Therefore, streamflow measurements taken at distances from the Foster Park gage do not represent conditions at the Foster Park gage itself. This has the effect of adding uncertainty to both the manual measurements and the rating curve estimated streamflows, because the manual measurements are used to generate the rating curve's stage-discharge relationship, and rating curve-estimated flows are based on stage measurements at the Foster Park gage. Due to the highly variable streamflow conditions in the vicinity of the Foster Park gage, it is especially important that streamflow measurement locations used for calibration are accurately represented in the model calibration process.

Upon inspection of model output, INTERA discovered that simulated streamflow differs by more than 2 cfs within only 200 feet upstream or downstream of the gage, and by as much as 5 cfs at 500 feet downstream (see **Figures 3-9** and **3-10**). Wet/dry survey results generally agree with these streamflow dynamics, with a consistent re-wetting of the channel immediately downstream of the Foster Park gage (UVRGA, 2022a). Note, from 2009 through 2016, nearly all manual streamflow measurements for low flows were taken downstream at an average of approximately 400 feet from the Foster Park gage or were reported without a specified measurement location. Figure 3-9 shows a chart of the streamflow measurement distance versus time (left) and a map view of the model grid and measurement distances (right). Because most streamflow measurements were taken downstream during the pre-2017 period, the stage-discharge relationship used to develop the rating curve for this period was not representative of streamflow at the Foster Park gage. Therefore, the rating curve-estimated streamflow used to calibrate the original model produced a bias that generally over-simulated streamflows at Foster Park because streamflow is generally higher downgradient. Around 2017, manual streamflow measurements were closer to or directly at the Foster Park gage, and, since then, the average measurement distance has been approximately 100 feet upstream (Figure 3-9). Therefore, the apparent over-simulation of baseflow at Foster Park during this post-2018 period found in the model verification (Section 2.1) was not due to a decline in the model performance; rather, it was because the measured dataset shifted to reflect actual gage and upstream conditions and thus lower flows. This finding helped refine the streamflow calibration process to ensure consistency between the simulated streamflow and the manual measurements by accounting for the distance from the Foster Park gage.

3.3.2 Summary of Streamflow Calibration Dataset Updates

The analysis of streamflow measurement distance effects on the model results led to refinement of the streamflow measurement calibration dataset to weight manual measurements taken either at the Foster Park gage or upstream. Weighting was applied to the calibration metrics of the model to favor more reliable observation datasets. Weighting is a statistical process applied in calibration where factors are assigned to residuals for specific observation datasets based on their relative precision and reliability. A weight equal to 1 is neutral, while weights greater than 1 are applied to more reliable datasets and weights less than 1 are applied to less reliable datasets (a weight of zero removes the dataset from the calibration). In addition, modeled streamflow outputs were extracted from the model cell located at the reported measurement distance to calculate streamflow residuals (difference between model simulated value and observed value) accurately. Downstream measurements were excluded from the calibration dataset due to (1) the uncertainty in model stratigraphy and lack of data to assess groundwater levels in this area and (2) groundwater management decisions being based on streamflow at the Foster Park gage.

Streamflow observations below 10 cfs were given higher weights to focus on the baseflow range in observations most relevant to the 2 cfs minimum threshold for the depletion of ISW sustainability indicator. The refined streamflow calibration dataset removed nearly all pre-2017 manual streamflow measurements, as they were either collected downstream of the Foster Park gage, had an unspecified measurement distance, or were >10 cfs. The only pre-2017 data included in the calibration dataset were several observations of zero flow during dry periods between 2013 and 2017.

An additional analysis of the streamflow dataset noted an unusual baseflow recession pattern for 2018 that the model could not simulate. The recession is unusually steep, and baseflow rapidly flattens out (for example, see USGS measured streamflow in Figures 3-2 through 3-5). Previous and subsequent years do not exhibit this same pattern. Additional inspection of the observation dataset indicated all gaged tributary inflows for the model input (gages 602B, 604, and 605) were flagged as either “estimated” or “poor” and appeared to be overestimating the typical shape of the recession curve (see Section 4.1.2 for additional detail). This portion of the streamflow data was deemed unreliable for calibration and was given a low weight in the calibration dataset (see Section 3.4).

3.3.3 Groundwater Level Calibration Dataset

All groundwater level observations used in the original model calibration were retained for the calibration update dataset, and additional data collected since then were included. Importantly, monitoring wells FP-MW-1 and FP-MW-4, located near the Foster Park gage, were instrumented after 2018 and provided new groundwater level observations adjacent to the Ventura River channel. Groundwater level data were assigned lower weights relative to the streamflow measurement data to focus the calibration update on improving the match to post-2018 low streamflow conditions at the Foster Park gage.

3.4 Setup of PEST++IES Analysis

The results of the sensitivity analysis and dataset updates previously described provided the framework for setting up the PEST++ IES calibration. Parameter groups were defined primarily for Sy and HK in the

Casitas Springs and Santa Ana zones (Figures 3-2 through 3-5), with parameter ranges prescribed to favor the calibration goal of improving the overall match to post-2018 observed baseflow. Weights were applied to the calibration datasets (see Section 3.3.2) to favor more reliable observation datasets.

Groundwater level observations were included in the calibration dataset but were assigned lower weights than streamflow observations. For each of the groundwater wells used in the calibration dataset, weighting was normalized by the number of observations per well so that each well contributed equally to the total residual associated with groundwater levels. The streamflow calibration dataset was updated due to multiple factors summarized in Section 3.1. Streamflow data were weighed to consider only manual measurements collected at or upstream of the Foster Park gage and <10 cfs. Within the streamflow calibration dataset, the weighting was scaled to the magnitude of measured streamflow to emphasize focus on baseflow conditions (**Table 3-1**). Note, rating-curve based continuous streamflow estimates were not used to assess the calibration fit.

Table 3-1. Foster Park streamflow observation weighting used for PEST++IES.

Measurement Direction from Gage Specified by USGS	Observed Streamflow Magnitude	Observation Weight Applied	Weighting Explanation
Downstream	All Flows	0	Located outside of basin - lack of bedrock elevation data and groundwater levels downstream of Foster Park
Unspecified (unknown location)	All Flows	0	Unknown measurement location
Upstream	0 < q ≤ 2 cfs	2.5	Emphasis on low flows. Not including observations greater than 10 cfs
	2 < q ≤ 5 cfs	1.5	
	5 < q ≤ 10 cfs	1.0	
	q > 10 cfs	0	
At Gage	0 < q ≤ 2 cfs	2.5	Emphasis on low flows. Not including observations greater than 10 cfs
	2 < q ≤ 5 cfs	1.5	
	5 < q ≤ 10 cfs	1.0	
	q > 10 cfs	0	
Observations made after 10-01-2019	All Flows	3	Post WY-2019 weights raised to steer IES towards matching key targets in later years
All observations between 04-01-2018 and 08-01-2018 (heavily estimated tributary inflows)	All Flows	0.1	De-weighted to account for estimated and poor rating tributary inflows during this period

PEST++IES iteratively runs several realizations of the model (perturbing parameters within a prescribed range) and identifies parameter combinations, which minimize the overall residual between simulated and observed data. The range of error associated with observation data was accounted for in the calibration process by assigning a zero residual when the modeled streamflow was within the reported measurement error range. The PEST++IES calibration was then configured so that, after computing the residual, the total error was rescaled such that 20% of the objective function was attributed to groundwater error and 80% to streamflow error. This approach balanced the relative influence of the two datasets, providing a calibration focus on streamflow conditions at Foster Park while maintaining a similar level of calibration to groundwater levels as the original model.

4.0 Calibration Results

Using the updated calibration datasets and weighting functions described in Section 3, PEST++IES was executed through a series of calibration runs to improve the match to observed data, with each model iteration building on the insights gained from previous iterations. Wider ranges of parameters were used in earlier iterations to explore the model parameter space more thoroughly, while later runs progressively narrowed parameter bounds based on results from both the sensitivity analysis and information gained from the early calibration runs. In addition, after each PEST++IES iteration, the best fit model realizations were qualitatively (visually) assessed relative to key groundwater well hydrographs and the measured streamflow at Foster Park. The spatial distribution of hydraulic conductivity and storage parameter fields were also visually assessed to ensure consistency with the hydrogeologic conceptual model. In total, roughly 20 iterations of the calibration were performed, each running the model hundreds of times. Once satisfactory fits to streamflow and groundwater targets were achieved, a final calibration run was setup in Monte Carlo[1] mode, using the best-calibrated model run from previous PEST iterations as the starting iteration and further refining the Casitas Springs zone. This allowed further exploration of the parameter spaces for a well-calibrated model run. The final calibrated model, referred to as the "updated model" in this TM, was selected from the Monte Carlo runs using calibration metrics described in the following subsections.

4.1 Modeled Streamflow Improvements

This section discusses the results of the updated model regarding streamflow measurements. The uncertainty in modeled streamflow due to the error in tributary inflows is also analyzed to provide recommendations for the future use of the model.

4.1.1 Updated Model Streamflow Results

The updated model shows an overall improved ability to match streamflow measurements at Foster Park in comparison with the original model. The improvement to simulating streamflow reflects the effectiveness of (1) the parameter adjustments made by PEST++IES during the calibration process, (2) the refinement of the streamflow calibration dataset described in Section 3, and (3) the other model updates described in Section 2.3.

Model performance in simulating streamflows at Foster Park was evaluated by comparing simulated and observed data. The residual is used as a calibration metric and is calculated by subtracting the simulated streamflow from the observed streamflow. Objective functions of Root Mean Square Error (RMSE),

[1] Monte Carlo refers to a method which randomly samples parameter values from a prescribed range.

Mean Absolute Error (MAE), Residual Sum of Squares (RSS), and two efficiency metrics commonly used in surface water modeling—the Nash-Sutcliffe Efficiency (NSE; Nash and Sutcliffe, 1970) and the Kling-Gupta Efficiency (KGE; Gupta and Kling, 2011)—use the residual to quantify the closeness of fit between simulated and observed streamflow. In general, a lower value for the objective function represents a closer fit between simulated and observed data; however, both NSE and KGE range from negative infinity to 1.0, with values closer to 1.0 indicating better performance. Across all metrics, the closeness of fit between simulated and observed streamflow for the updated model was improved in comparison with the original model (**Table 4-1**).

Table 4-1. Streamflow residual objective function metrics for the original and updated models. Metrics were calculated using observations (i.e., manual streamflow measurements at or upstream of Foster Park) for flows less than or equal to 10 cfs.

Objective Function	Equation	Original Model	Updated Model
RMSE[1]	$\sqrt{\sum_{i=1}^{n}\frac{(obs_i - sim_i)^2}{n}}$	3.1	1.5
MAE[1]	$\frac{1}{n}\sum_{i=1}^{n}\lvert obs_i - sim_i\rvert$	0.82	0.85
RSS[1]	$\sum_{i=1}^{n}(obs_i - sim_i)^2$	1,261	288
NSE[1,2]	$1 - \frac{\sum_{i=1}^{n}(obs_i - sim_i)^2}{\sum_{i=1}^{n}(obs_i - \overline{obs})^2}$	-0.53	0.63
KGE[2,3]	$1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2}$	-0.06	0.82

[1] obs_i is the i[th] observed value and sim_i is the i[th] simulated value produced by the model, n is the number of observations, See Sections 3.1 and 3.3.2 for details on the observed values used in the model calibration.

[2] The best possible value of NSE and KGE is 1.0 (Nash and Sutcliffe, 1970; Gupta and Kling, 2011).

[3] r is the Pearson correlation coefficient, α is a term representing the variability of prediction errors, and β is a bias term (Gupta and Kling, 2011).

Figure 4-1 compares simulated and observed streamflow at manual measurement locations for the original and updated models. The continuous output of streamflow at the Foster Park gage is included as solid lines for reference, and the color-coded points are simulated streamflow at the measurement location distance from the gage, which are used for the residual calibration metrics (see Table 4-1 above). The observed streamflow dataset includes the measurement error range as vertical lines. These results visually show a clear improvement between the original and updated model results and are verified with the quantification of the residuals included in Table 4-1 above. Note, there are limited observed data available prior to 2018 due to most of the manual measurements being located downstream or location is unknown. For the purpose of qualitative analysis, **Figure 4-2** compares simulated and observed streamflow including the downstream and unknown manual measurements. In this comparison, it is noted that the original model generally overestimated pre-2018 flows due to being calibrated to rating curve estimated streamflow data rather than manual streamflow measurements including their distance from the gage (see Section 3.3.1). The influence of measurement distance is particularly evident in 2010, 2011, and 2012, when most measurements were taken approximately 500 feet downstream from the Foster Park gage (Figure 4-2). This plot also visually shows a clear improvement between the original and updated model results, with the updated model points closer to the observed points than the original model points.

The updated calibration demonstrated a clear improvement in predicting streamflow at Foster Park in comparison with the original model. By shifting the calibration dataset from rating-curve estimates to manual streamflow measurements and explicitly accounting for the measurement location, the model is now calibrated to a dataset that more closely represents actual streamflow conditions in the vicinity of the Foster Park gage. This improved the statistical performance of the model and resolved the apparent post-2018 discrepancy identified during the model verification task (see Section 2.1).

4.1.2 Analysis of Tributary Inflow Error on Model Results

Following the calibration update of the original model, INTERA assessed the impact of error in tributary inflow measurement and estimation used for streamflow input to the model (i.e., Ventura County gages and ungaged tributaries, respectively; see Figure 2-2) using the results of the critical review of streamflow data (see Section 2.2; INTERA and Bondy, 2024). Model scenarios representing the upper and lower error bounds for the inflows were developed to evaluate how the range in error of inflows affects model results. These model runs provide a spread of possible streamflow at Foster Park given the range of error for the tributary inflows.

The range of error for the three gaged tributary inflows was based on measurement ratings described in the INTERA critical review of streamflow data (2024): 5% for “good,” 10% for “fair,” and 25% for “poor” (see example Figure 2-3). These ratings were attributed to measurements at the three gaged tributaries (602B, 604, and 605A, managed by Ventura County). For all ungaged tributaries, the highest error rating (25%) was applied uniformly; however, this likely had insignificant impact on the model results during baseflow because the ungaged tributaries typically do not flow during the dry season.

In addition to the measurement error, there are periods of “estimated” streamflow when gages are offline (INTERA, 2024). Typically, the largest residual between simulated and measured streamflow can be traced to these periods of “estimated” records in the tributary inflows. For example, water year 2018 had extended periods of estimated streamflow for multiple gages during baseflow recession, which may overestimate the inflows for the model. **Figure 4-3** shows streamflow curves for the tributary gages 602B, 604, and 605A for water year 2018. Here, the estimated streamflow is problematic because it was generated by linearly interpolating between manual measurements, which does not follow the form of a typical baseflow recession. The result is an input to the model that misrepresents actual streamflow and understates the steepness of recession curves, making inflows significantly overestimated in this example.

The impact of the estimated inflow on simulated streamflow is evident in the hydrographs presented in **Figure 4-4**, which shows (1) the simulated streamflow with tributary error range (green line with gray band) and (2) simulated streamflow with tributary error range (orange dots with error bars) and observed streamflow (black dots with error bars) at manual measurement locations. Note, extended periods of estimated streamflow are identified for at least one gaged tributary (i.e., 602B, 604, or 605A) during most years (see Figure 4-4 and Attachment A in INTERA, 2024). Across the model period (2005 through 2024), 12% of the streamflow data from gage 602B is estimated, 38% of gage 604 is estimated, and 14% of 605A is estimated. As discussed above, during the 2018 recession, flows at gages 602B and 604 were both estimated May through August, and gage 605A had poor measurements and was intermittently estimated (see Figure 4-3). Consequently, the model oversimulated streamflow compared with the manual measurement observed dataset, and the calibration was unable to match the shape of the baseflow recession for 2018. The range of error for estimated gaged tributary data is likely to be much higher than the 25% prescribed for this analysis; however, this was unquantifiable due to the lack of documentation available from the streamflow data records.

Figure 4-4 shows that the range of errors in tributary inflows is particularly influential on model results during certain years such as 2016, the latter half of 2018, and 2021, when simulated flows exhibit a wider spread of results; these correspond to periods when tributary inflows were largely rated as "poor" or "estimated." This analysis provides additional context for evaluating the potential uncertainty associated with model inputs and its impacts on simulated streamflow for the Foster Park gage.

To summarize, the updated model results are constrained not only by the calibration process but also by the quality of the data used as inputs and observation targets (i.e., manual measurements). Two primary sources of uncertainty based on estimated ranges of error were identified in this data: (1) uncertainty in the manual streamflow measurements used for calibration (i.e., Foster Park gage) and (2) uncertainty in the tributary inflows for the Ventura River (i.e., Ventura County gages and ungaged tributaries). No additional uncertainty associated with model parameters was explored in this calibration update; therefore, INTERA recommends a comprehensive predictive uncertainty analysis for the model to provide a probabilistic likelihood of minimum threshold exceedance when using the model to assess streamflow depletion. The model inherently has a nonunique solution, meaning there are multiple combinations of parameters that will produce the same closeness of fit to the observed data. Exploring the potential range of model results for equally calibrated models will provide a clearer understanding of how model results impact management decisions for the Basin.

4.1.3 Model Fit to Groundwater Level Measurements

The primary objective of the calibration update was to improve the model's ability to represent measured streamflow at Foster Park during low-flow conditions while maintaining an acceptable fit to groundwater levels across the Basin. Overall, the calibration update achieved this goal. When model results are evaluated against all groundwater level targets, the updated model preserves the quality of the groundwater level calibration, with both RMSE and MAE objective functions slightly decreasing relative to the original model (**Figure 4-5**). Two areas where visible changes in simulated groundwater levels were noted are the Robles/Mira Monte and Santa Ana zones. The scaled RMSE and MAE (ratio of the model error metric to the range of observed water levels) values for the updated model were 1.9% and 1.4%, respectively—well below the industry standard of 10% (Spitz and Moreno, 1996; Rumbaugh and Rumbaugh, 2017) and show a slight improvement compared with the original model, which was 2.1% and 1.6%, respectively.

Simulated and observed groundwater level hydrographs for key wells within the Basin are shown on **Figure 4-6**. Overall, the model results show acceptable fits to the observed data at the key wells. One exception is at well 04N23W29F02S, which diverged slightly from observed values in comparison with the original model. This response is attributed to the adjustments made during the calibration update, where groundwater levels were raised upstream to reduce simulated streamflow at Foster Park via the decrease of HK. Although this represents a slight local deterioration in model fit to observed groundwater levels, the degradation in fit at a single groundwater level monitoring location was outweighed by the improvements in representing streamflow dynamics at Foster Park, as well as the improvement in groundwater level fit when all observations are considered. In addition, as can be seen in the hydrograph for 05N23W33B03S, groundwater level data for the post-original model calibration period (i.e., verification period, post-2018) shows a discrepancy between simulated and observed data. Verification of other non-key hydrograph wells with continuous groundwater level data measured during this period also shows some discrepancies, which indicates the model may require additional calibration to improve the match this data. Additional investigation and review of recently measured groundwater levels to determine whether recorded values are pumping or static is also recommended.

4.2 Calibrated Model Parameters

The primary changes to the original model parameters during the calibration update were to the HK and Sy in the Santa Ana and Casitas Springs zones. Parameter bounds were set within reasonable values that aligned with the known measured hydraulic data and the hydrogeologic conceptual understanding for the Basin. The distribution of parameters is shown in **Figures 4-7** and **4-8** and summarized below:

- Sy was overall decreased in the Santa Ana zone and increased in the Casitas Springs zone (Figure 4-7).
- HK was overall slightly decreased in the Santa Ana zone (Figure 4-8).
- HK was overall decreased in the upper Casitas Springs zone and increased in the lower Casitas Springs zone (Figure 4-8).

The zonal relative changes in parameters for the updated model are consistent with the sensitivity analysis findings (Section 3.2). At a finer scale, HK was increased or decreased at pilot point locations in focused areas to improve the match to groundwater levels, potentially accounting for bedrock thickness. In addition, localized areas of Sy changes may reflect storage response from bedrock, which was not explicitly simulated in the model. Nonetheless, the final distribution of parameters was still consistent with the hydrogeologic conceptual model for the Basin and was considered acceptable.

5.0 Conclusions and Limitations

The original model for the Basin was originally calibrated to groundwater level and streamflow data through 2018. Following model verification to post-2018 data, the model required a critical review of streamflow data and calibration update. Model updates were incorporated, and a sensitivity analysis was performed to guide the setup of the calibration update. The calibration data for streamflow and groundwater levels were updated and refined, and the PEST++ IES software was utilized to automate the calibration. Both quantitative (simulated versus observed residuals) and qualitative (visual comparison of data) assessments of groundwater levels, streamflows, and calibrated model parameters guided the selection of the best model fit to observed data. The effort for the calibration update improved the model's ability to represent low-flow conditions at the Foster Park gage while maintaining an acceptable fit to groundwater levels across the Basin. The following conclusions can be drawn from this TM:

- *The Ventura River channel geometry is highly dynamic.* The modeling code used to represent streamflow (MODFLOW Streamflow Routing [SFR] package) can only simulate fixed conditions and channel geometry. As was observed following the January 2023 flood, the location and conditions of the river channel can change dramatically following stormflows, and the current model cannot represent transient channel conditions. However, the analysis conducted for the model concluded that results are not significantly impacted by changes in channel geometry.
- *Model updates addressed several factors hindering the model's performance:* The conversion of the model to daily stress periods, updating modeled pumping rates, adjusting streamflow inputs, modifying the bedrock surface, and addressing solver issues provided an improved model to be used for sensitivity analysis and calibration update.
- *Sensitivity analysis provided a focused approach for calibration update:* a high-level sensitivity analysis showed which parameter adjustments and areas of the model impacted modeled streamflow and groundwater levels and set the foundation for focused calibration setup.
- *The calibration dataset was updated to be the most representative and accurate measured data:* Critical review of the USGS streamflow measurements identified that most manual measurements were collected at a distance from the Foster Park gage, and model results change depending on this distance from the gage. In addition, rating curve estimated streamflow is highly uncertain and inconsistently updated. By excluding rating curve measurements, accounting for distance in manual measurements, and assigning a measurement-specific range of errors, a more accurate and representative calibration dataset was developed for the calibration update. The groundwater level calibration dataset was also expanded to include the most recent available data for the Basin.
- *The calibration update improved the model's ability to match streamflow measurements*: Using the original model with incorporated updates, an updated calibration dataset, and an automated calibration program (PEST++ IES), the model calibration was updated and overall reduced the error in modeled streamflow at Foster Park. Calibration objective functions (i.e., RMSE, MAE, KGE, NSE) all improved relative to the original model, and the updated model better represented both low-flow conditions and seasonal baseflow recessions for the Foster Park streamflow data.
- *The calibration update preserved a good match to an expanded dataset of measured groundwater levels:* Groundwater targets from the original model were updated, and small improvements were made to Basin-wide RMSE and MAE objective functions.
- *Uncertainty in modeled streamflow inputs was assessed:* The calibration update incorporated an updated tributary inflow dataset, and insight into the quality of the measured streamflow data provided a range of error, which was applied to the inputs for the updated model. This produced a potential range for model results based on the upper and lower bounds of error for inflows, which informed the recommendation for a comprehensive predictive uncertainty analysis of the model.

The simulated streamflow for the final updated model and the associated uncertainty based on the range of error estimated for the tributary inflows is presented in Figure 4-4 and discussed in Section

4.1.2. The range of simulated streamflow associated with the error in the tributary inflows indicates that the model requires additional predictive uncertainty analysis to quantify the probability of minimum threshold exceedance when it is used to estimate depletion of ISW. Because UVRGA is responsible for addressing depletion due to groundwater pumping causing streamflow to fall below 2 cfs and any depletion when undepleted flows are <2 cfs, the predictive uncertainty of simulated streamflow needs to be accounted for when depleted streamflow approaches the minimum threshold. Incorporating a quantification of predictive uncertainty of the model will provide an optimal assessment of undesirable results. Nonetheless, this study recognizes the importance of additional data collection points to verify sources of error in streamflow measurements, and the installation of the UVRGA gage at Camilo Cielo is a key data point to enhance the understanding streamflow dynamics in the Basin.

5.1 Model Limitations

Several limitations were recognized or emphasized based on the work, as follows:

- *Tributary inflows present a large source of uncertainty for the model*. While gaged tributaries were assigned measurement-based uncertainty ratings, periods of "estimated" flows may introduce far greater error than can be represented by the maximum of 25% applied to the range of error. Currently, the model inputs for inflows from ungaged tributaries do not impact streamflow during dry seasons; however, they are estimated inputs that may be an inaccurate representation of the Basin hydrology. Model results may be impacted if ungaged tributaries have the potential for inflows during dry conditions.
- *Manual streamflow measurements collected at a distance from the Foster Park gage present multiple challenges*. A reported location "500 feet downstream" may be imprecise, and, based on the modeled streamflow, small deviations in location can shift the corresponding model cell and introduce variability in streamflow. Consistent and well documented flow measurements will ensure the model is representative of actual flow conditions and that the model is used appropriately for decision making and calibration. Downstream streamflow measurements were removed from the calibration dataset due to the lack of available data concerning the aquifer and groundwater levels in this area, which is located outside of the Basin. Information on depth to bedrock, groundwater levels, and streamflow in this area would help remove this limitation and expand the calibration dataset.
- *Limited data are available for bedrock information within the model area.* As identified in the original calibration of the model, surface water and groundwater flows are strongly influenced by bedrock elevations and geology. The model is representative of the scale of data available; however, the available logs are insufficient to characterize the bedrock surface accurately in several areas. The calibration of HK and Sy is currently compensating for the lack of detailed bedrock information for the model. Fracture flow within the bedrock is likely not a limitation for the model, but a water quality analysis could help characterize whether bedrock groundwater contributes to the alluvial aquifer.

These limitations highlight that, while the calibration update represents an improvement to the original model, opportunities remain to refine both the model and the supporting datasets. More frequent and precisely located streamflow measurements at Foster Park, additional lithologic and groundwater level data to constrain conditions downstream better, and improved characterization of tributary inflows would all strengthen future calibration efforts.

5.2 Recommendations

The final work product described in this TM is an updated calibration for the UVRGA model. This updated model significantly improves the ability to simulate groundwater/surface water interaction and manage groundwater use with respect to the ISW sustainability indicator. Additional insight was gained into the uncertainty and limitations of the model, which led to some recommendations, which are discussed as follows:

1. Ongoing collection of streamflow measurements should be consistent and well documented to ensure the model is representative of actual flow conditions and is used appropriately for decision making and subsequent updates. The current documentation of manual streamflow measurements available via the USGS website is very important for assessing the model's ability to match streamflow at the Foster Park gage; however, additional documentation on the rating curve methodology specific to the Upper Ventura gage 11118500 is recommended. Additional documentation of the methods used to measure the distance of manual measurement locations from the Foster Park gage would help the accuracy of comparing simulated streamflow to measurements. Streamflow data collection at other active gages in the Basin (i.e., Ventura County, UVRGA, and DWR) should also maintain documentation consistent with USGS procedures. INTERA recommends ongoing engagement with gage owners and operators to clarify and enhance current documentation and ensure sufficient information is collected for streamflow measurements and estimation methodology.
    a. The new gage at Camilo Cielo owned and operated by UVRGA is a key data point to enhance the understanding of streamflow dynamics in the Basin. Operation of this gage will reduce many of the uncertainties associated with relying on two gages upstream of the basin. INTERA recommends the data collection and documentation are consistent with USGS methodology.
2. Due to the high variability in manual measurement location at the Foster Park gage, INTERA recommends that USGS or another entity complete a synoptic streamflow study consisting of periodic concurrent streamflow measurements made at various locations upstream and downstream of the USGS Foster Park stage sensor. This study would improve the understanding of localized streamflow variability and quantify the impact of streamflow measurements taken at different locations on the rating curve estimated and reported gauge flows.
3. Based on the results presented in Section 4, INTERA recommends that a more detailed uncertainty analysis be conducted to quantify the overall predictive uncertainty of the modeled streamflow and assessment of depletion. The analysis would provide a probabilistic likelihood of streamflow depletion exceedance. The updated model is a nonunique solution, meaning there are multiple combinations of parameters which produce the same closeness of fit. The recommended uncertainty analysis would utilize the calibration update results presented in this TM to address the potential outcomes under calibration-constrained ensembles of model realizations.

4. INTERA recommends additional characterization of the bedrock to increase the accuracy of groundwater/surface water interaction. Boring logs provide the most accurate information to characterize the bedrock surface; however, geophysical methods may provide a more continuous dataset to help interpret areas without boring logs. In addition, water quality analysis comparing deep and shallow groundwater samples can provide insight into the source of groundwater and the exchange between bedrock and alluvial groundwater.
5. This study achieved the overall goal of improving the model's ability to match streamflow observations while preserving the match to groundwater level observations. However, the assessment of the new groundwater level data acquired since the original model calibration indicates the potential for additional improvement to match groundwater levels. Section 4.1.3 identifies well 05N23W33B03S, which has continuous measurements indicating a discrepancy between simulated and observed groundwater levels. Continuous groundwater level measurements that were not available during the original calibration require additional review and verification to determine whether the model requires additional calibration.

6.0 References

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FIGURES

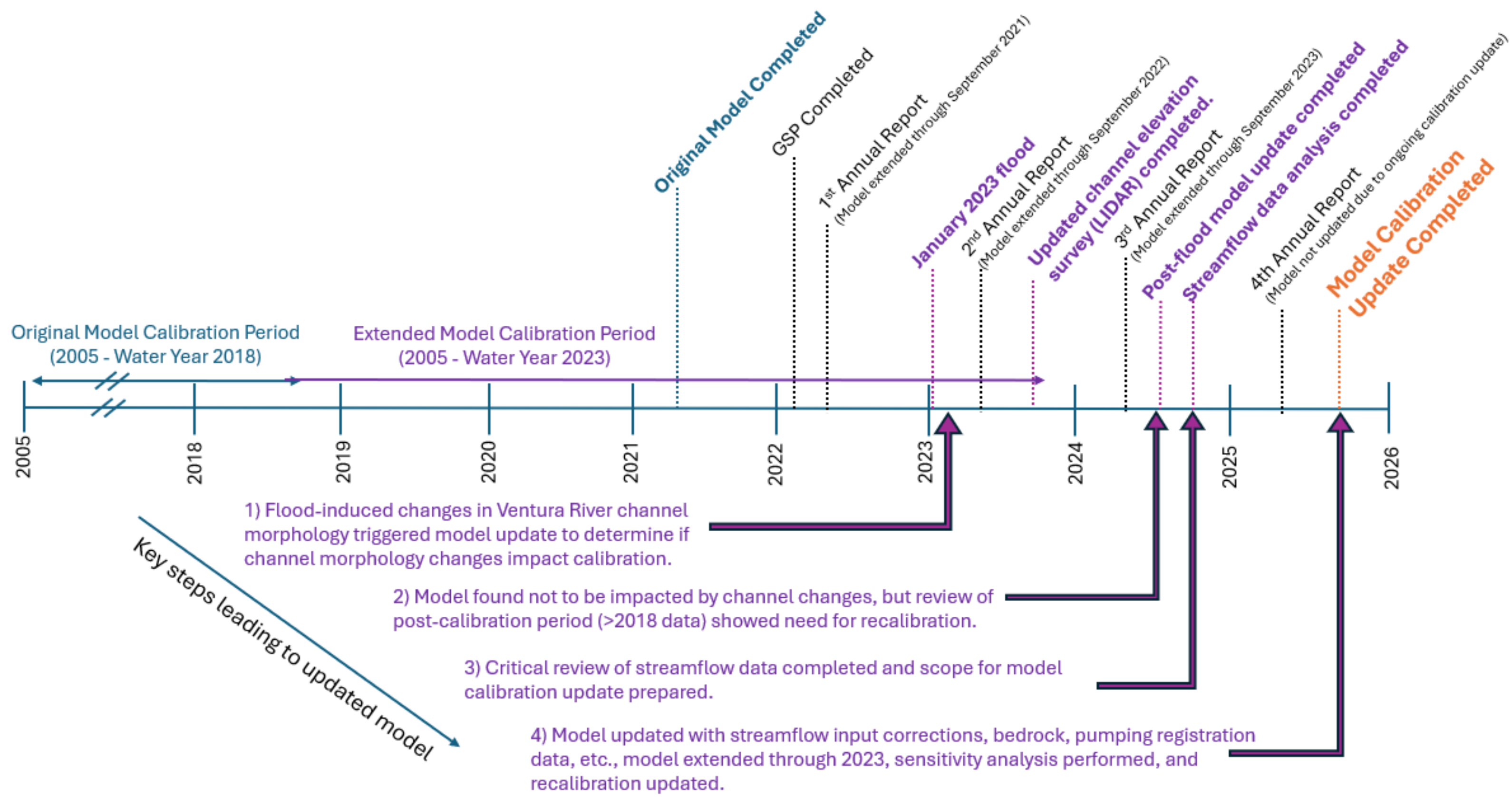


Figure 2-1. UVRGA model development timeline.

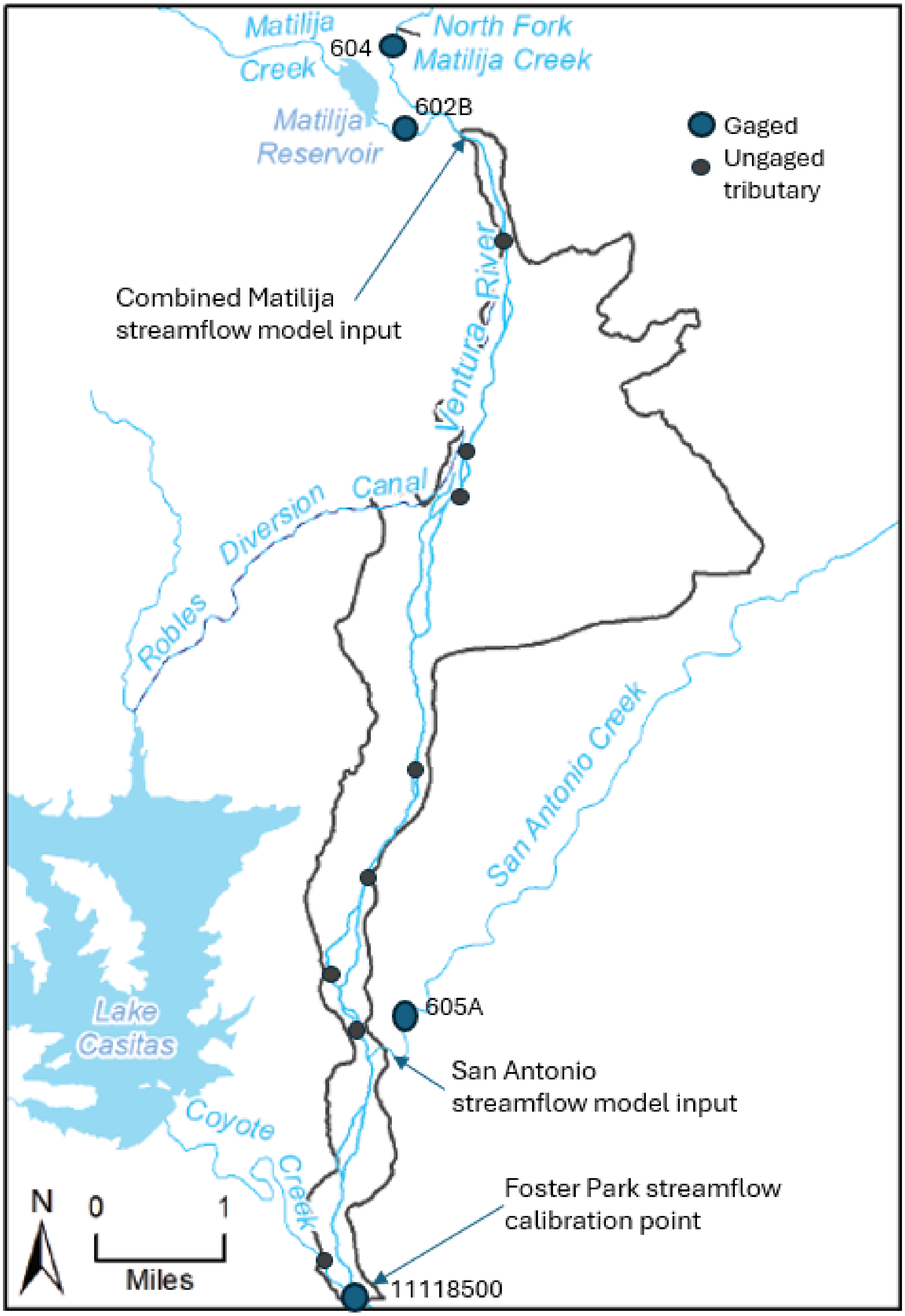


Figure 2-2. Stream gages and ungaged tributary locations in the Basin for the model input and calibration.

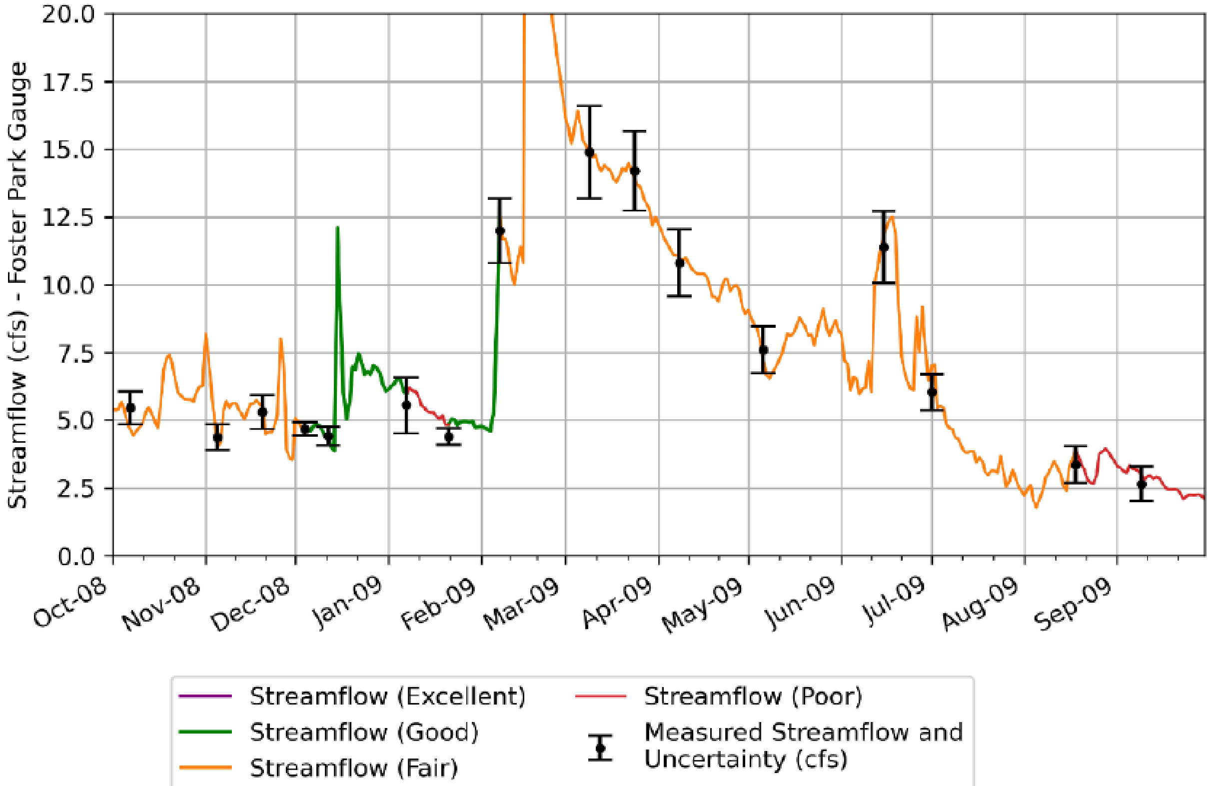


Figure 2-3 Example hydrograph for Foster Park gage 11118500 showing measured and estimated streamflow with quality ratings and range in measurement error.

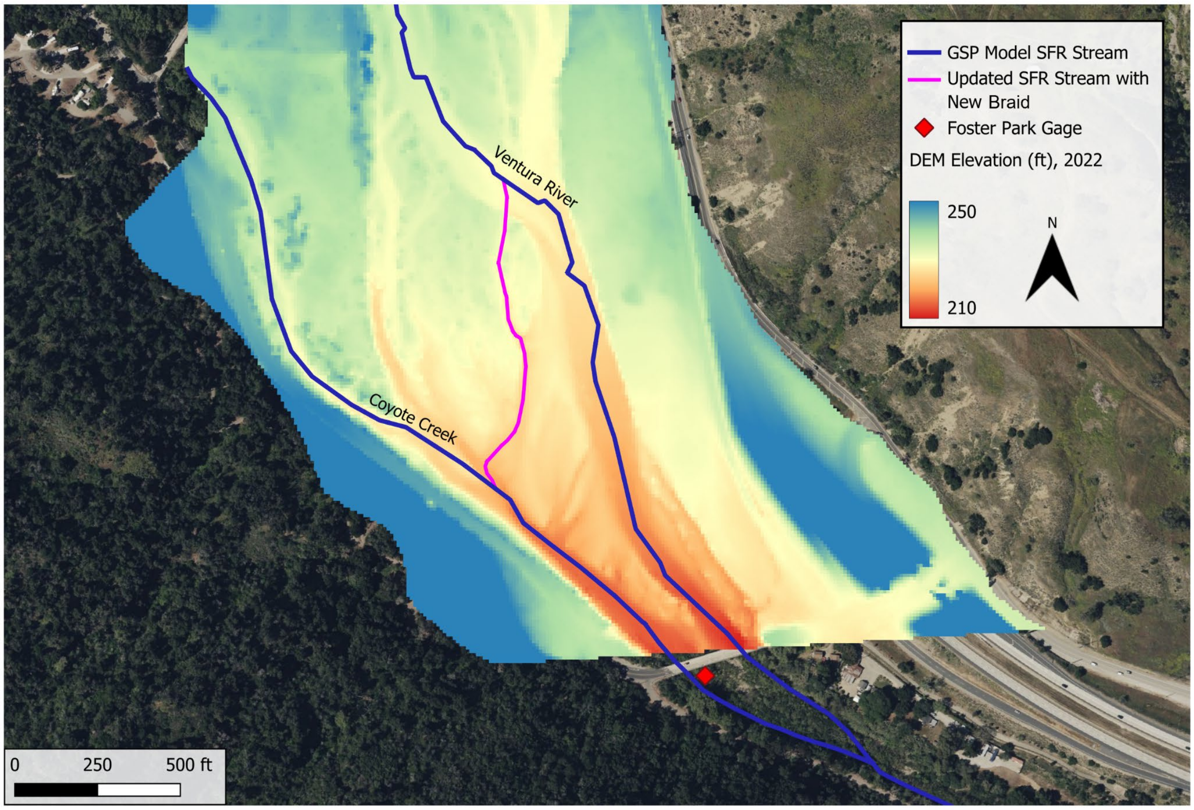


Figure 2-4. Updates to the modeled Ventura River channel braids and Coyote Creek confluence location.

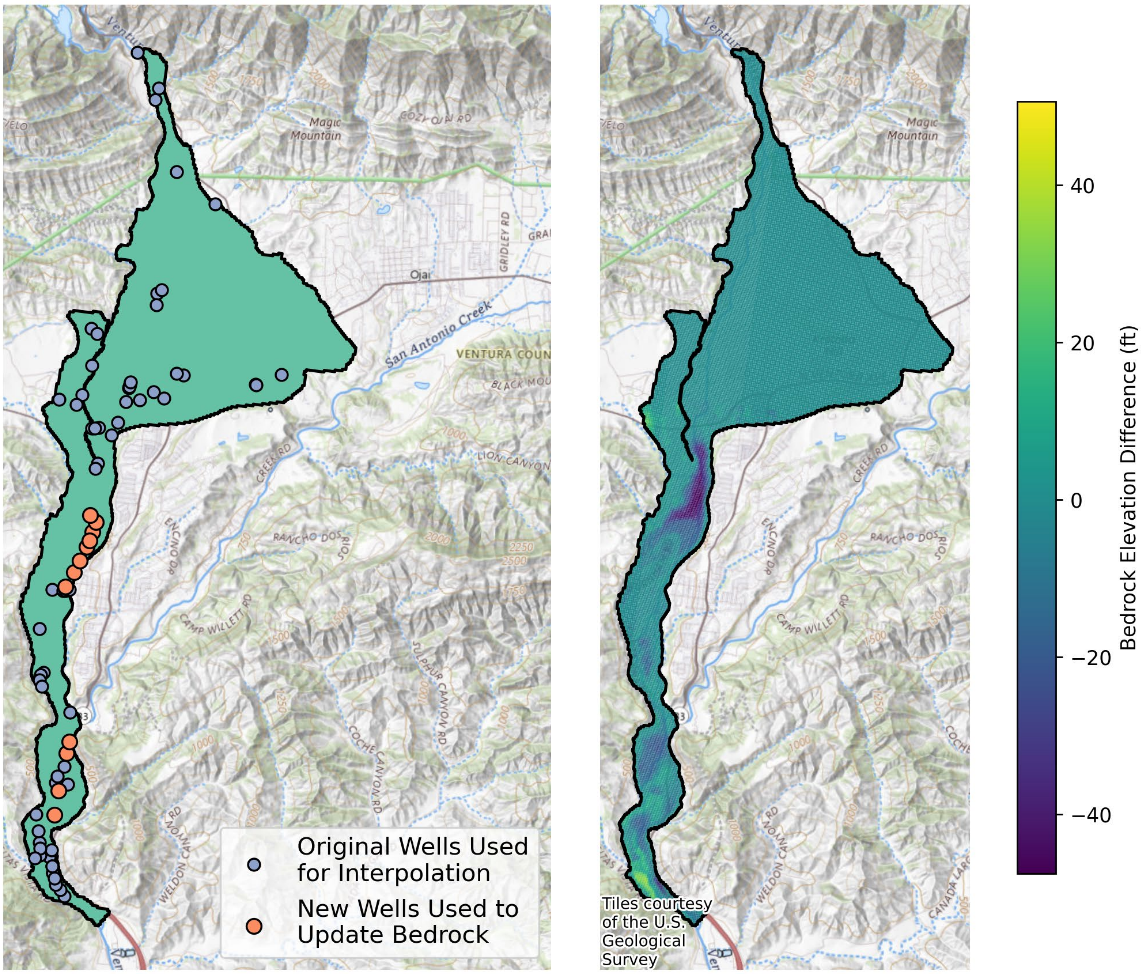


Figure 2-5. New well data and adjustments to modeled bedrock surface.

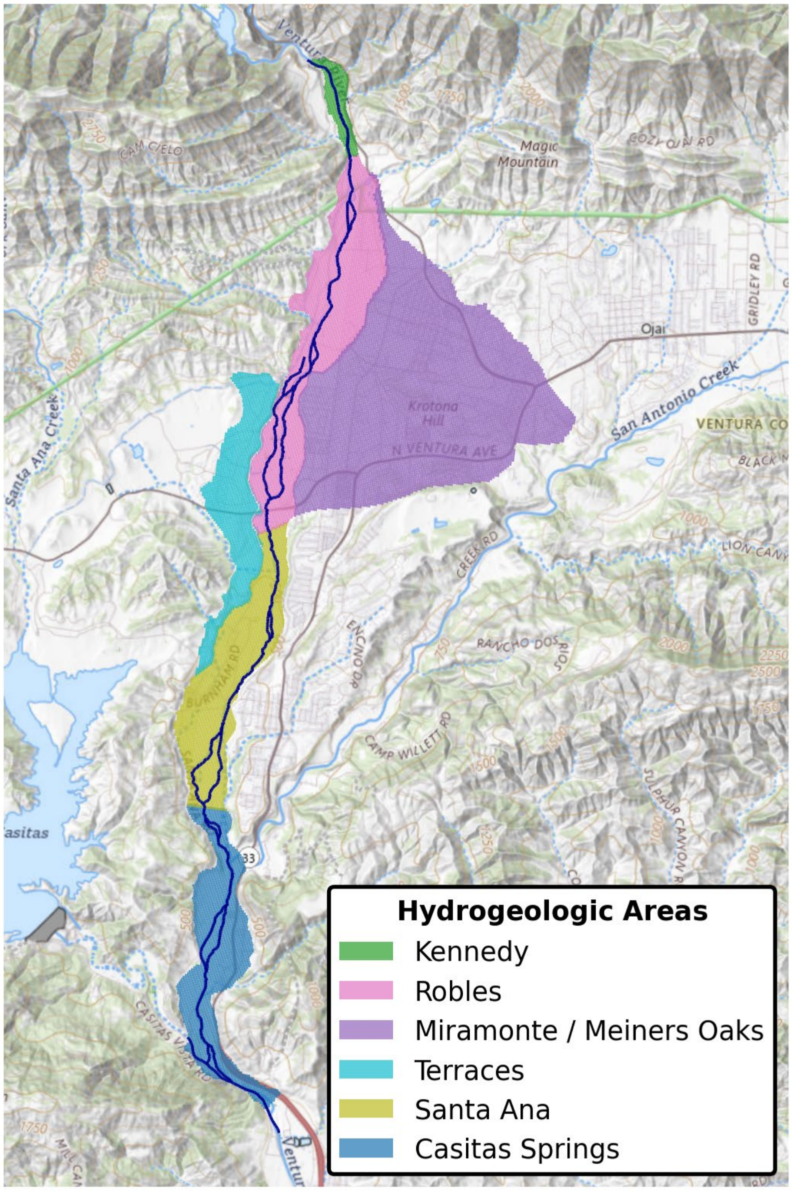


Figure 3-1. Hydrogeologic zones of the Basin.

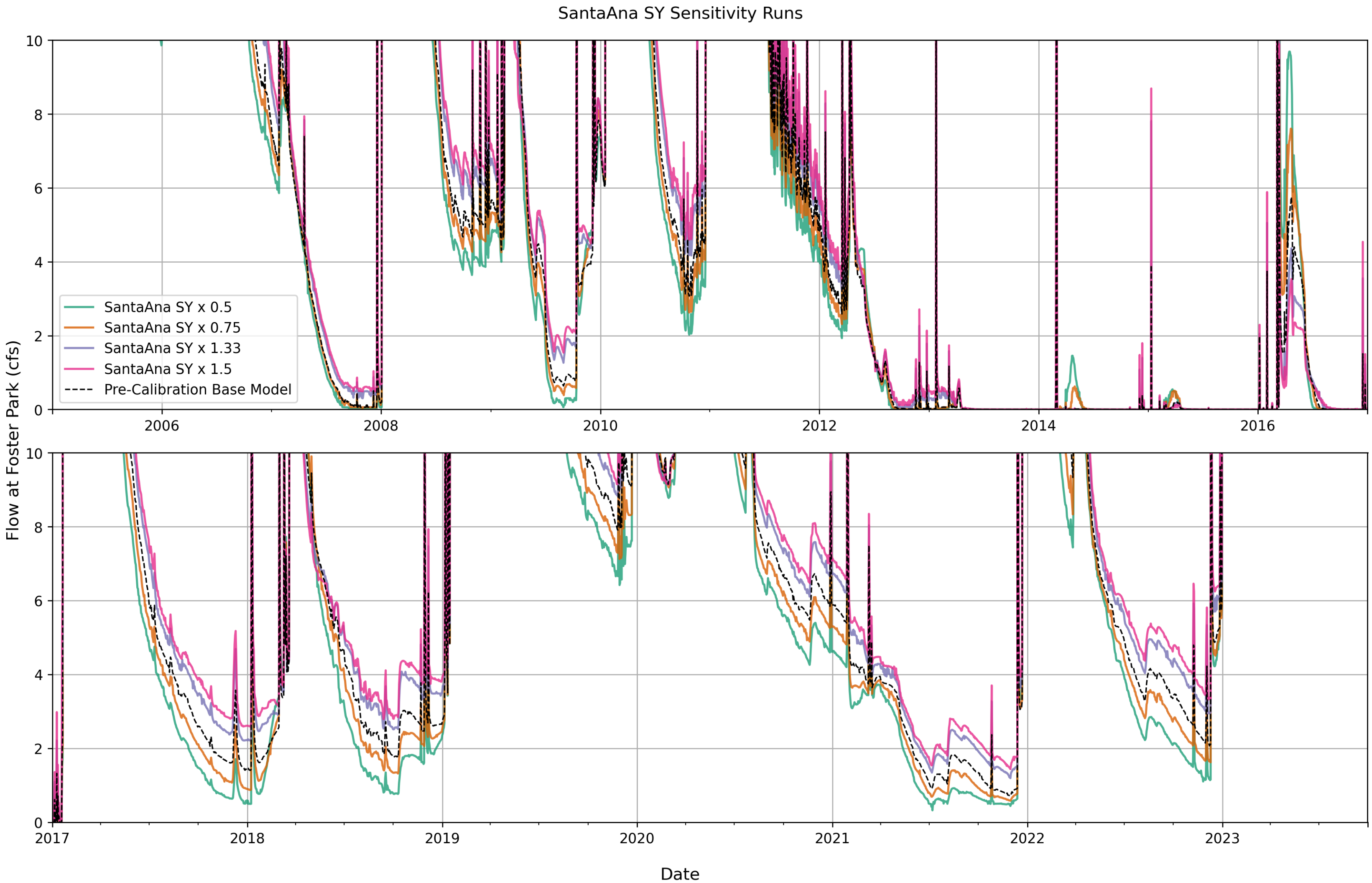


Figure 3-2. Simulated streamflow (at Foster Park gage) sensitivity to changes in specific yield for the Santa Ana zone.

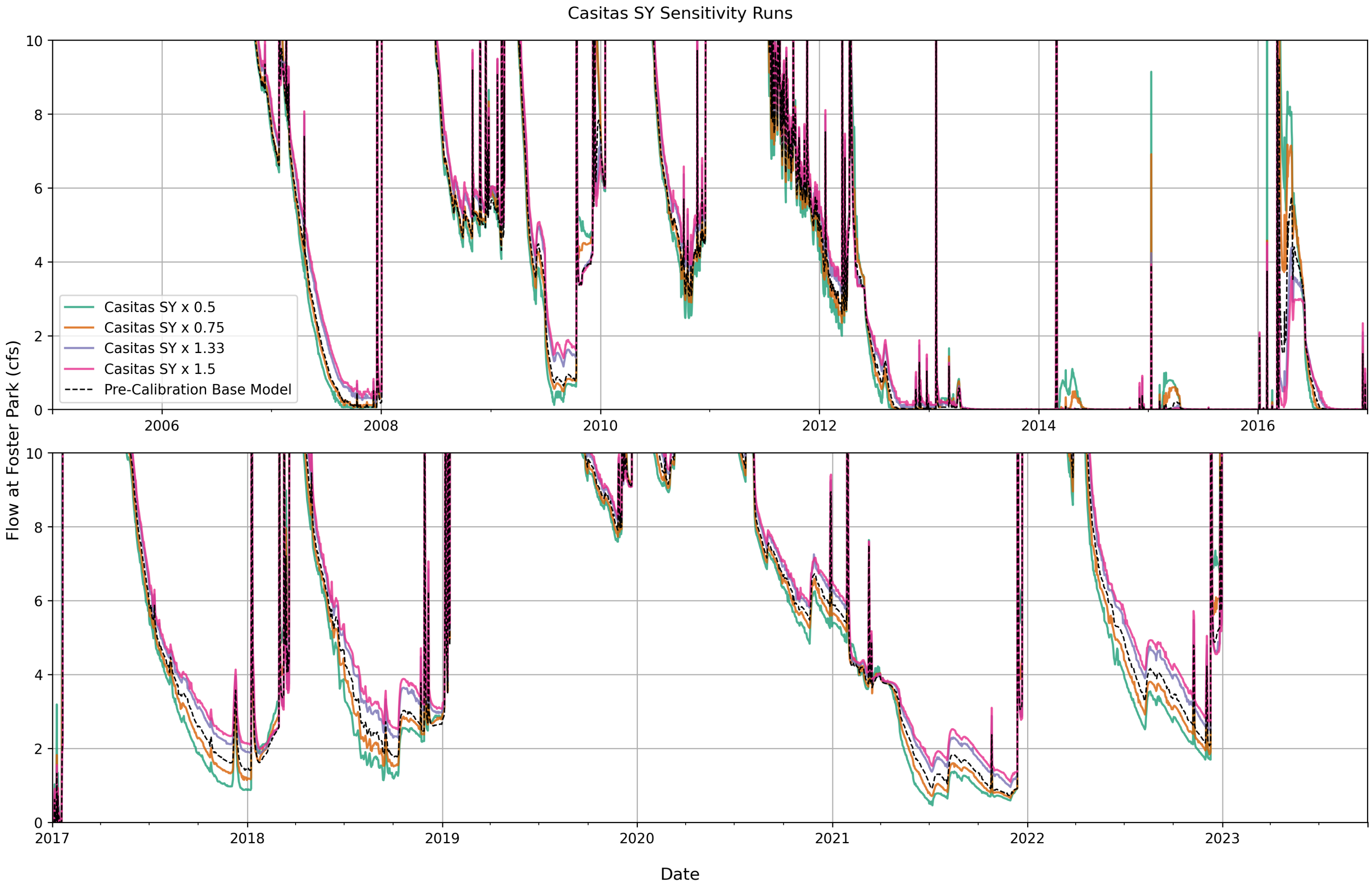


Figure 3-3. Simulated streamflow (at Foster Park gage) sensitivity to changes in specific yield for the Casitas Springs zone.

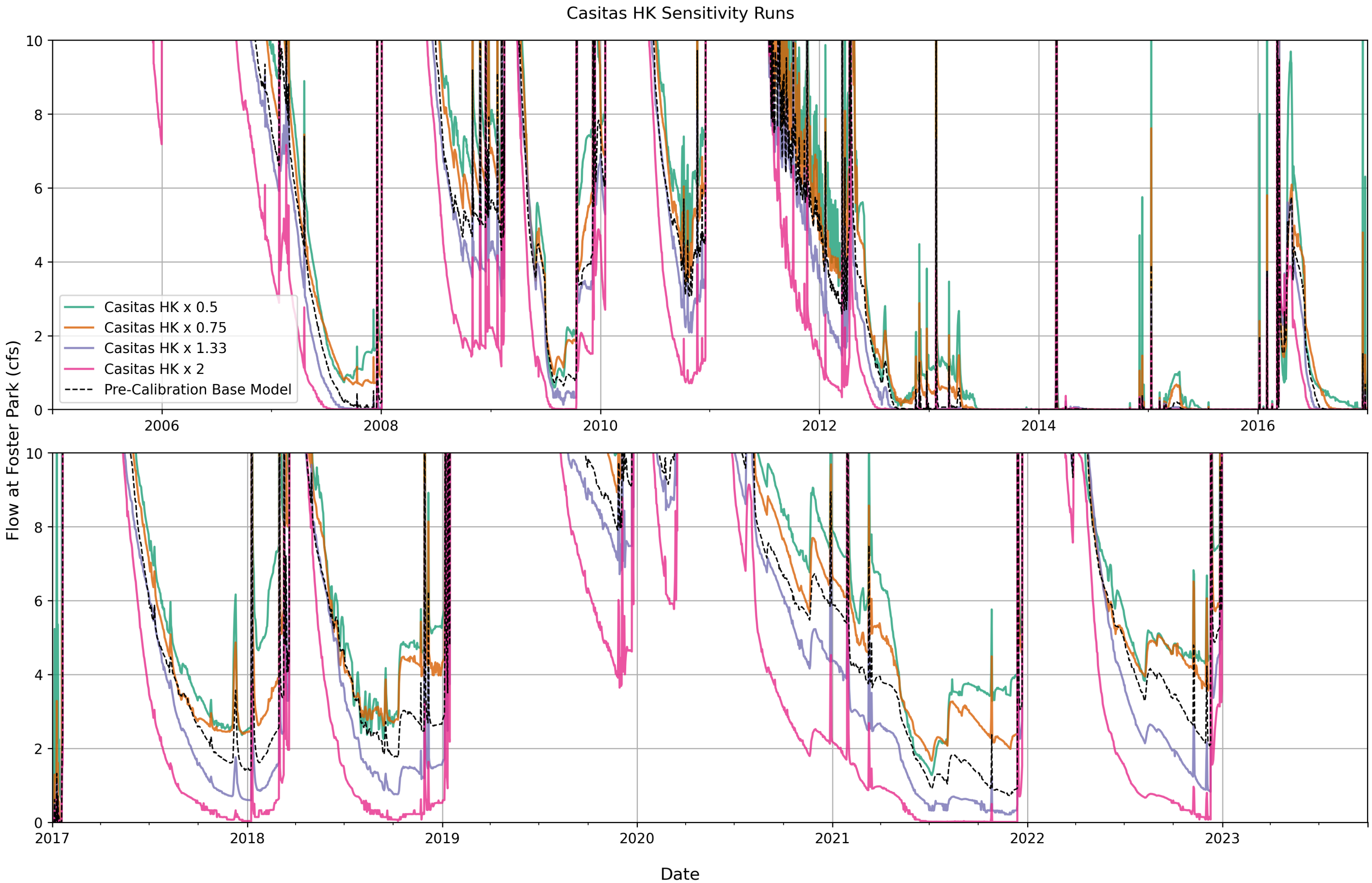


Figure 3-4. **Simulated streamflow (at Foster Park gage) sensitivity to changes in HK in the Casitas Springs zone.**

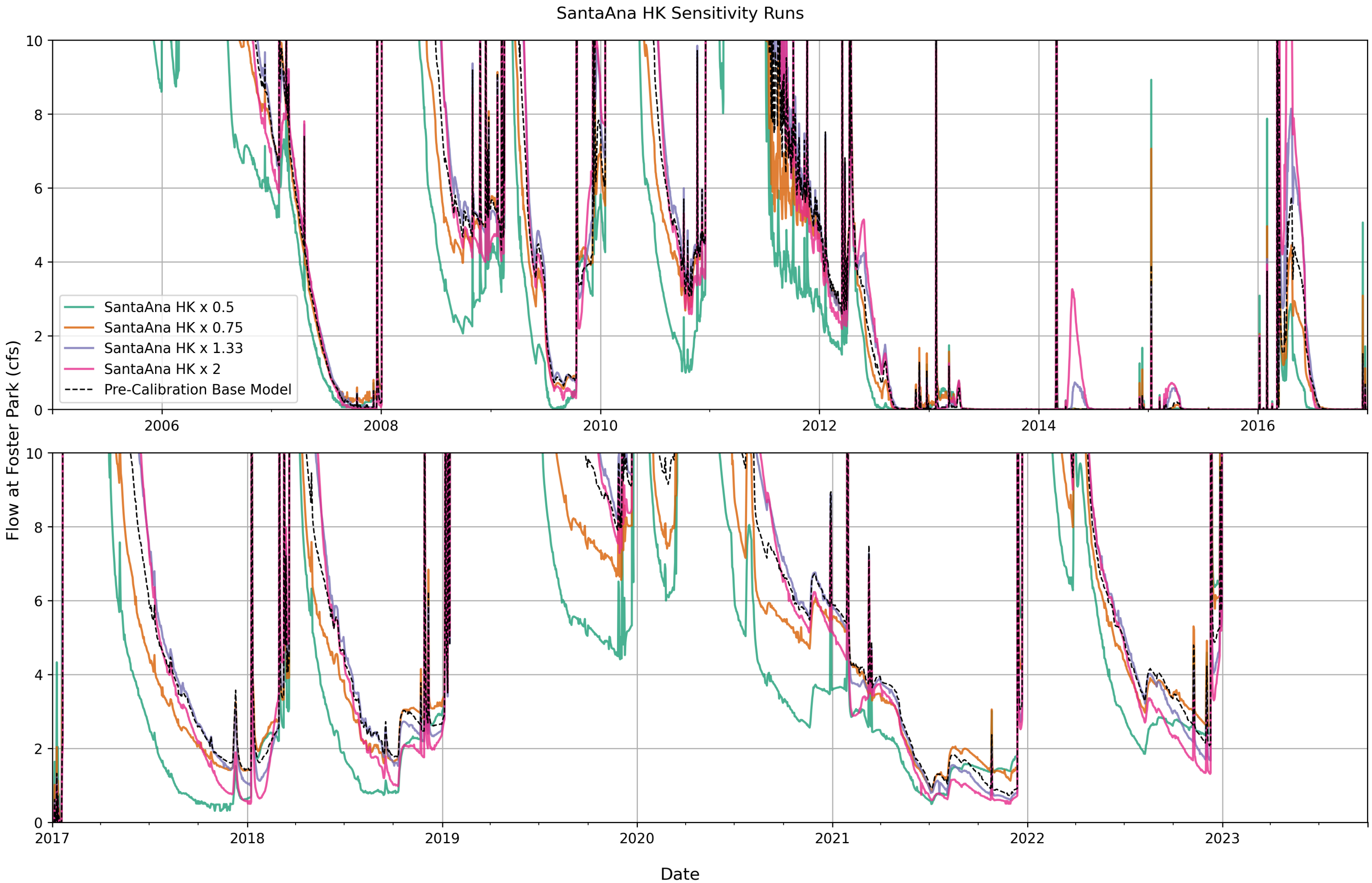


Figure 3-5. Simulated streamflow (at Foster Park gage) sensitivity to changes in HK in the Santa Ana zone.

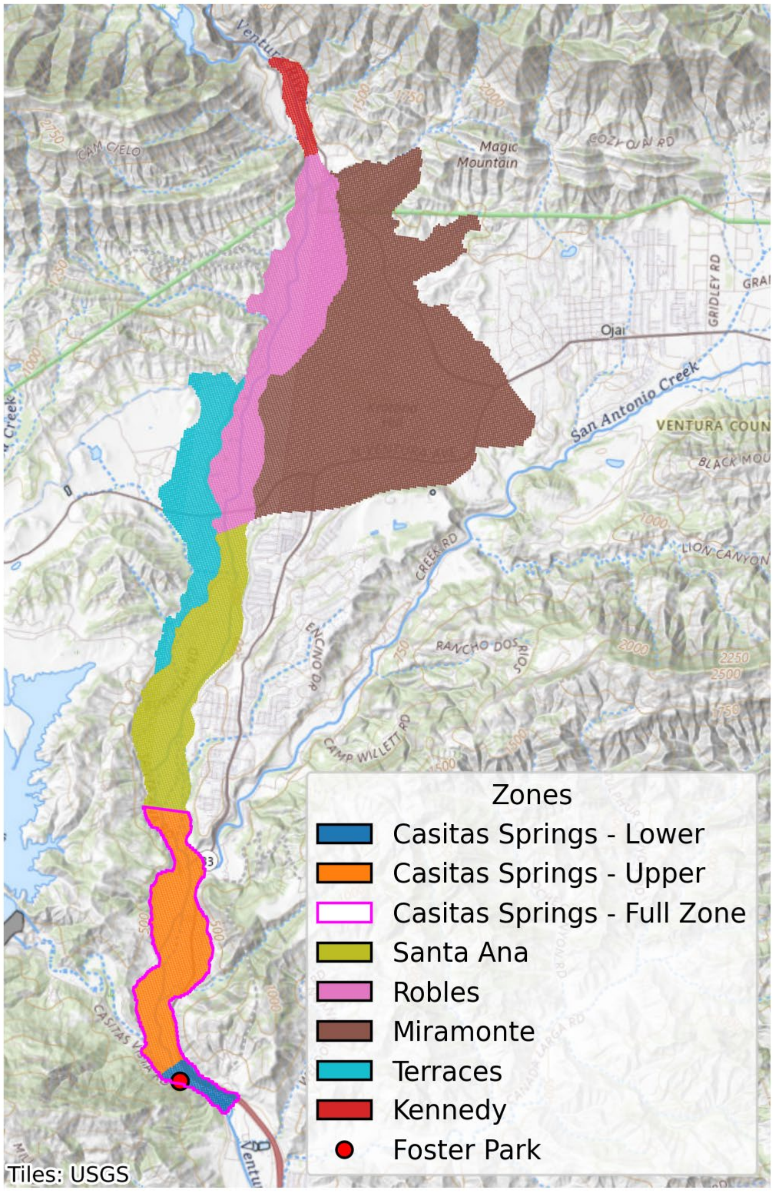


Figure 3-6. Casitas Springs zone with upper and lower split.

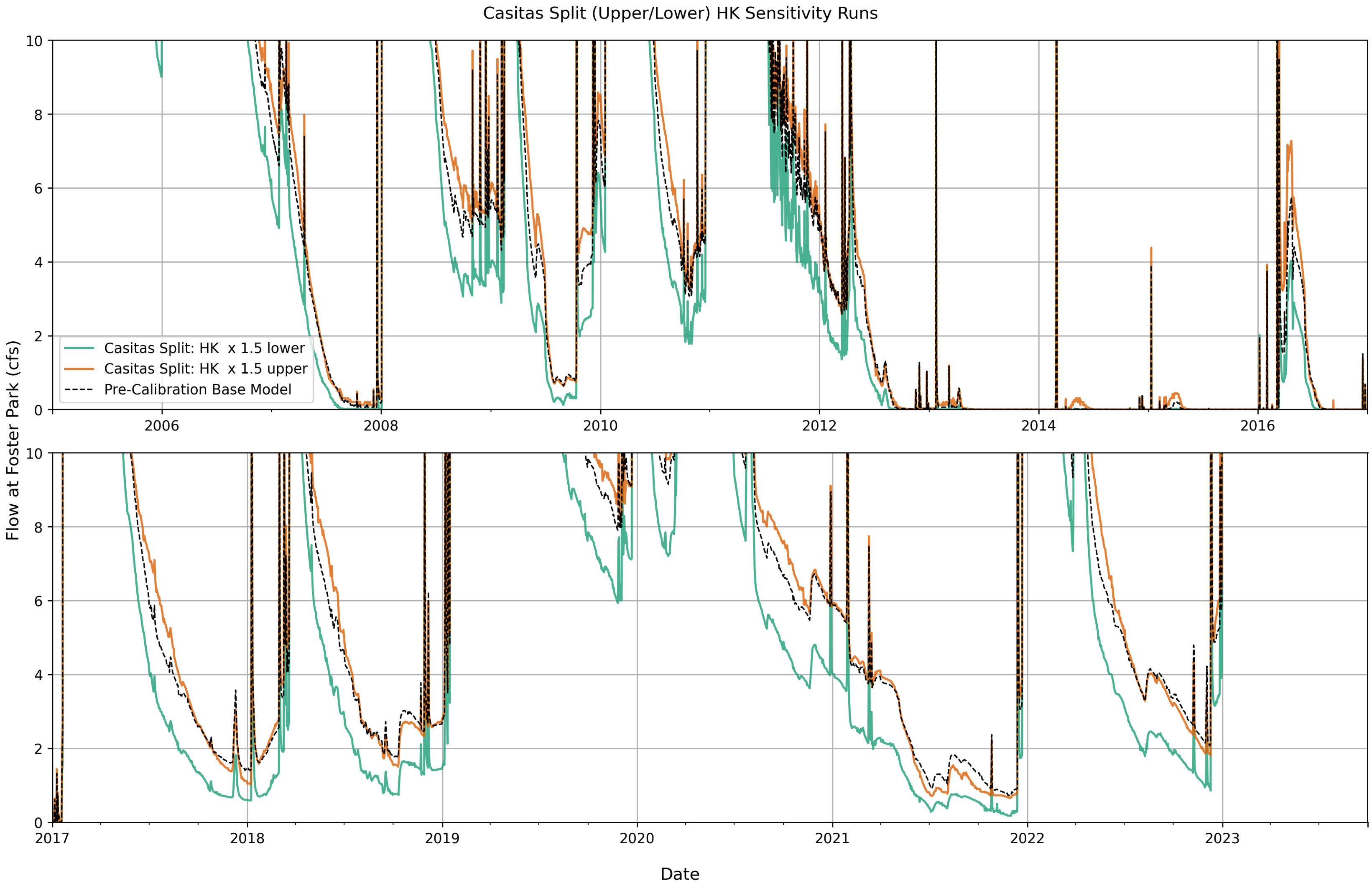


Figure 3-7. Results of upper and lower split of Casitas Springs zone sensitivity runs for HK.

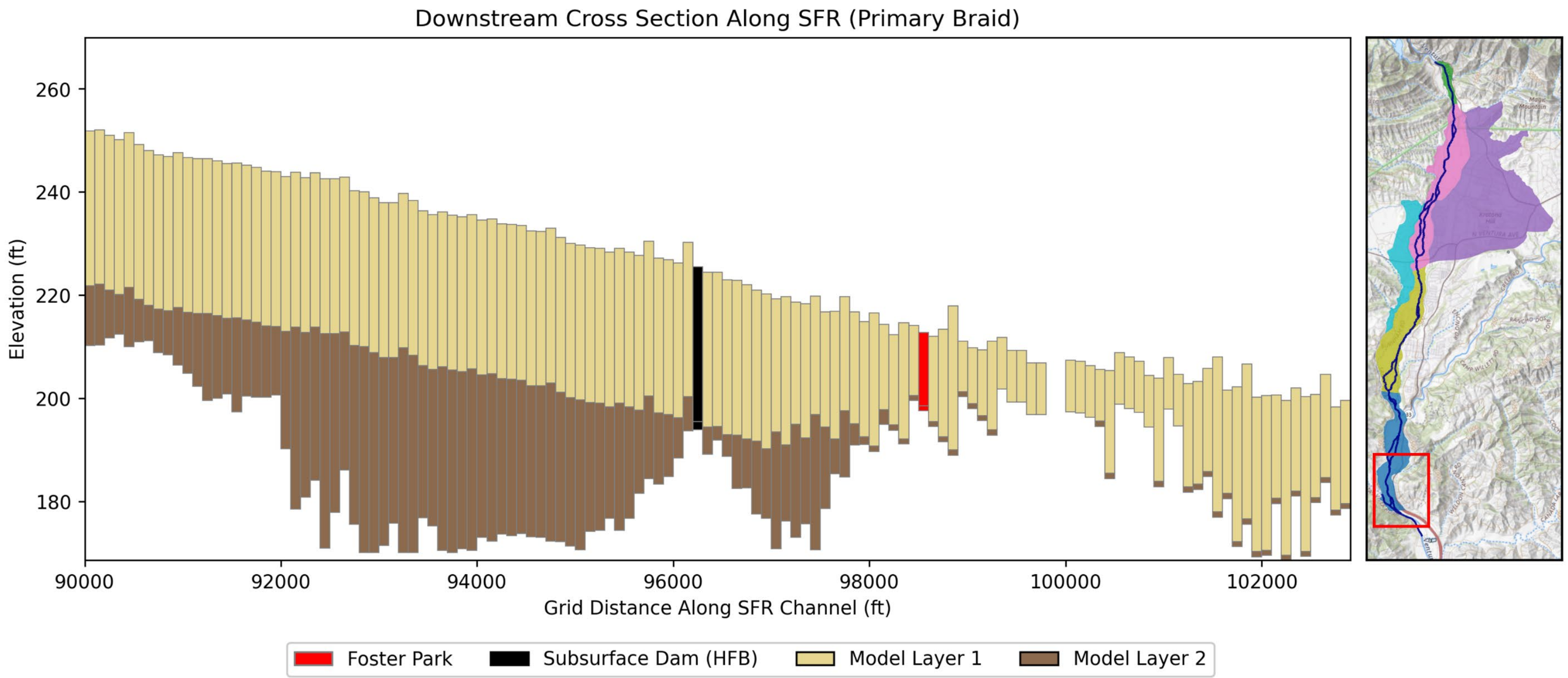


Figure 3-8. Cross-sectional view of the model grid along the Ventura River channel near the Foster Park gage.

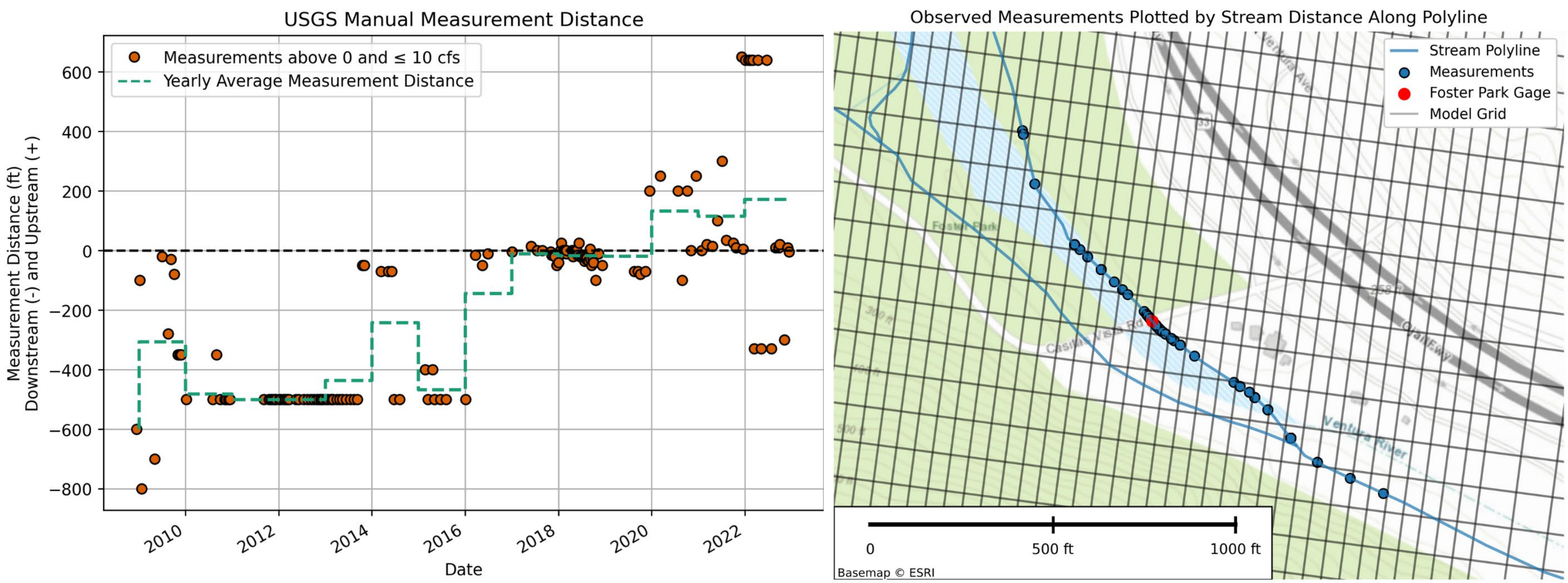


Figure 3-9. Chart of the streamflow measurement distance versus time (left) and a map view of the model grid and measurement locations (right).

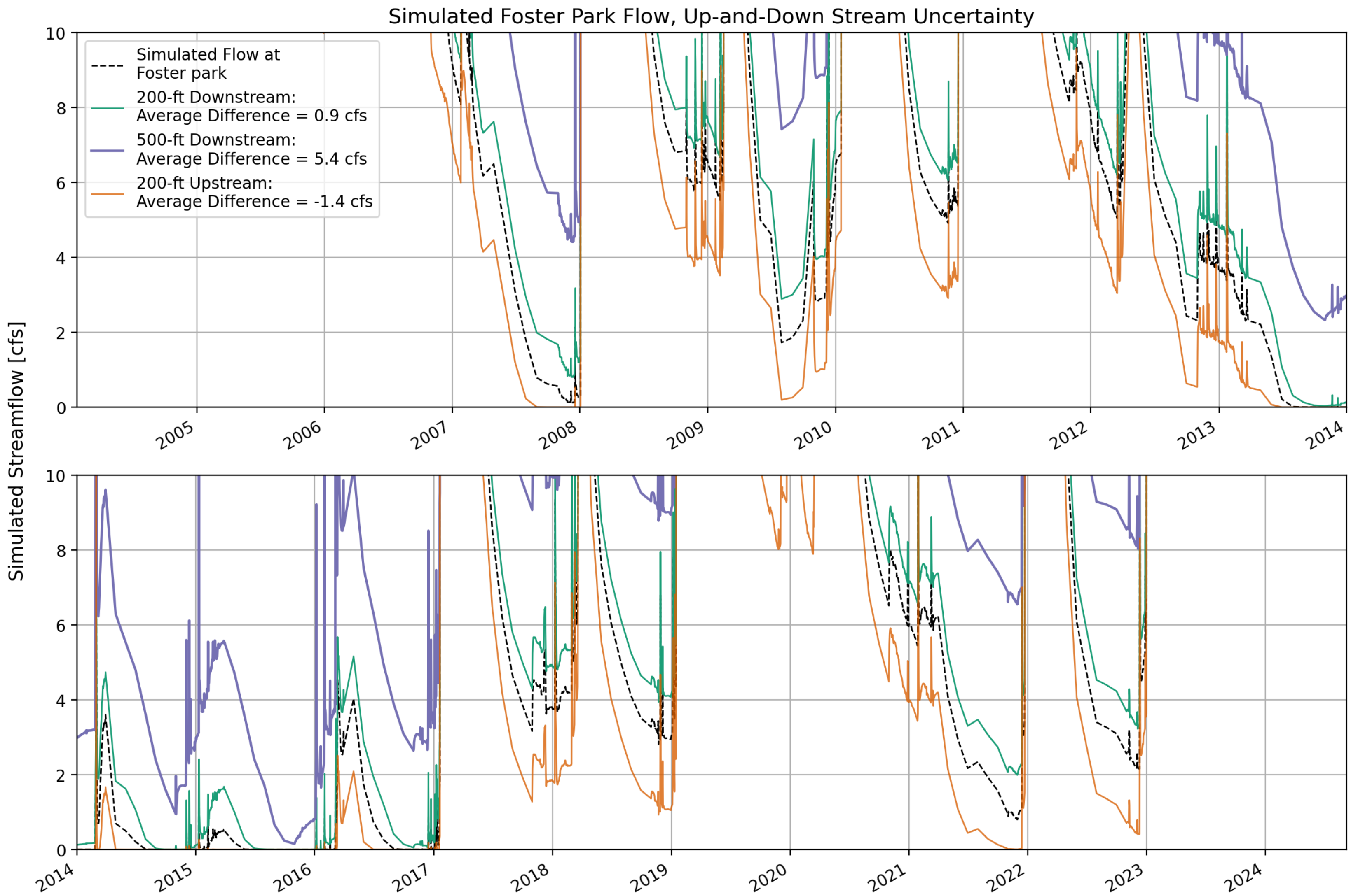


Figure 3-10. Sensitivity analysis results for simulated flow 200 feet upstream and downstream of the Foster Park gage and 500 feet downstream of the gage. Average difference values were calculated for flows less than or equal to 10 cfs.

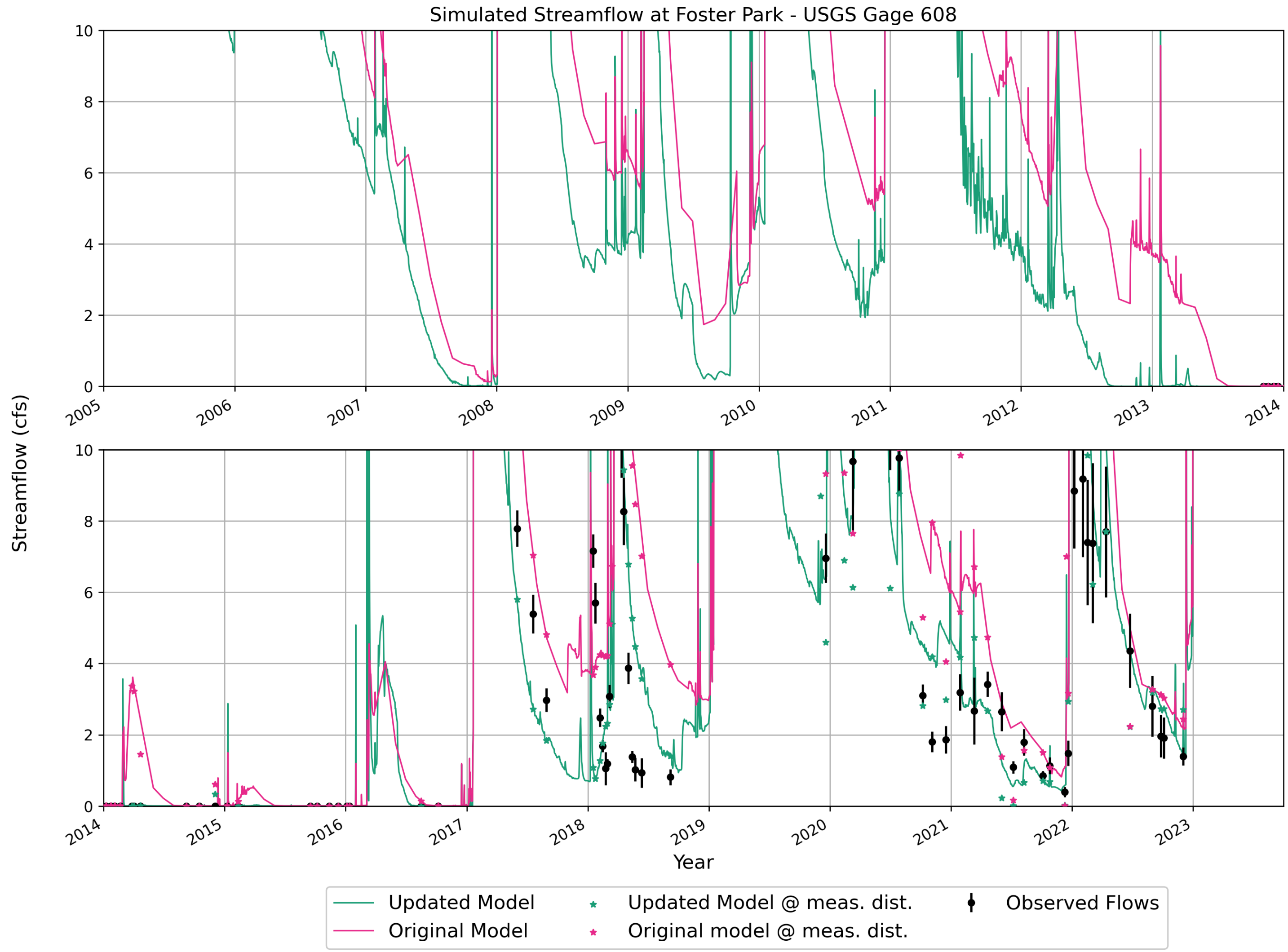


Figure 4-1. **Original and updated model simulated streamflow at Foster Park gage (colored lines) and at measurement location (colored dots), compared with observed streamflow at measurement location with range in error (black dots with bars).**

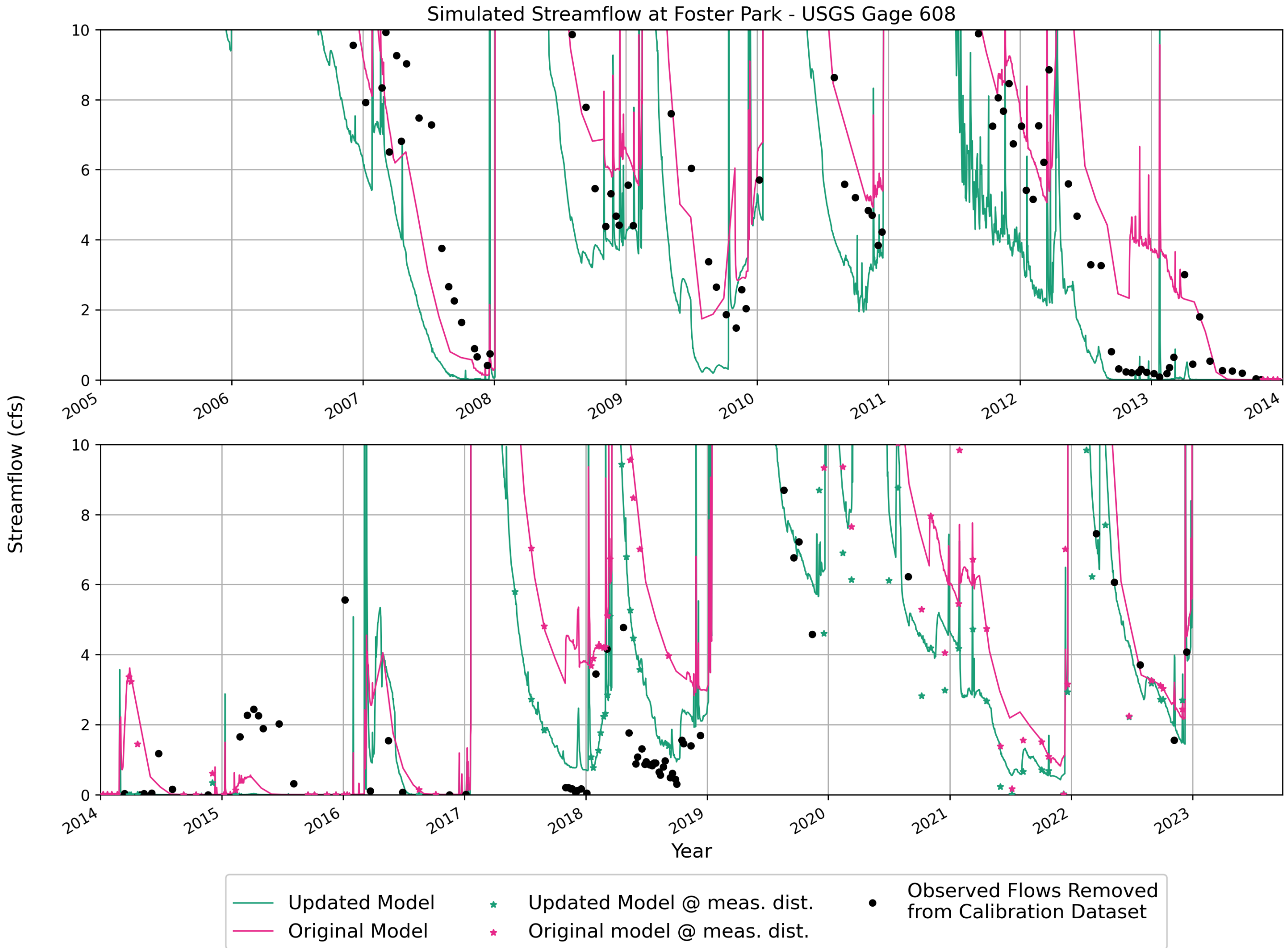


Figure 4-2. Original and updated model simulated streamflow at Foster Park gage and at measurement location compared to observed streamflow measurements that were removed from the calibration dataset. Observations without corresponding simulated data (i.e., colored dots) have an unknown distance; therefore, the simulated flow is set at the Foster Park gage.

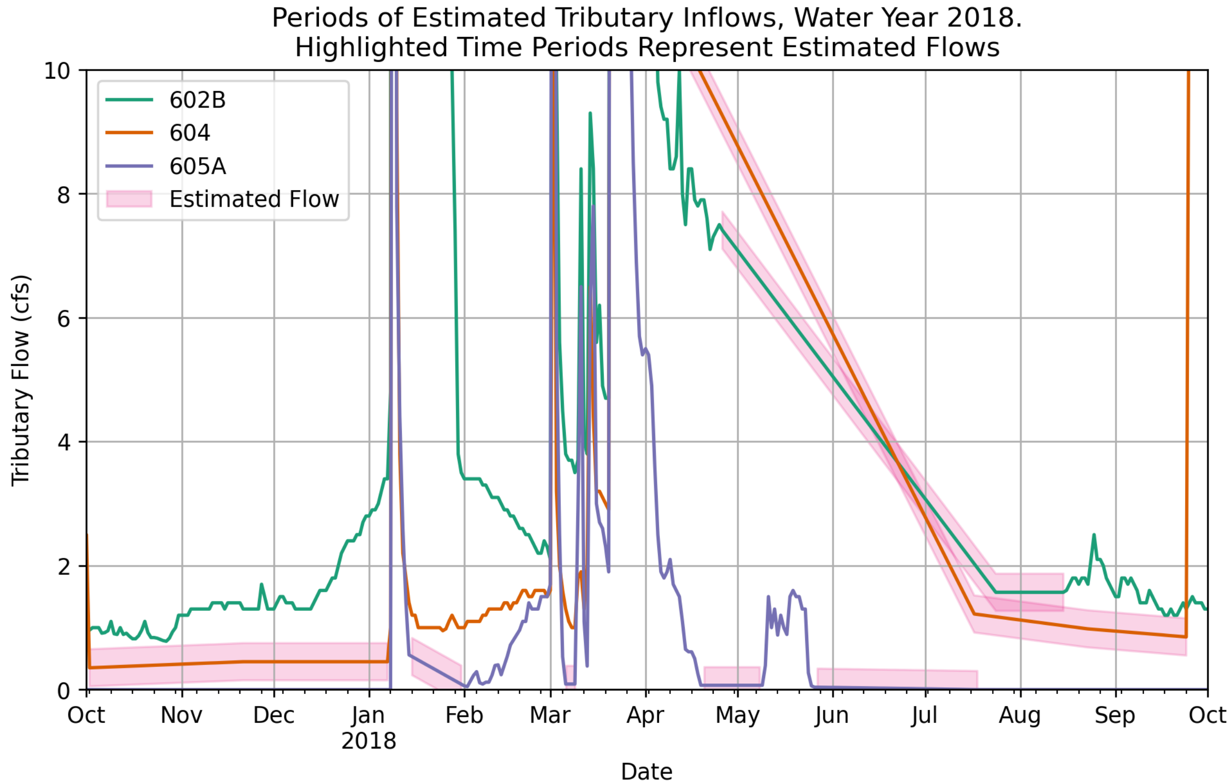


Figure 4-3. Streamflow curves for tributary gages 602B, 604, and 605A during water year 2018. Pink highlight indicates period of data qualified with "estimated" streamflow.

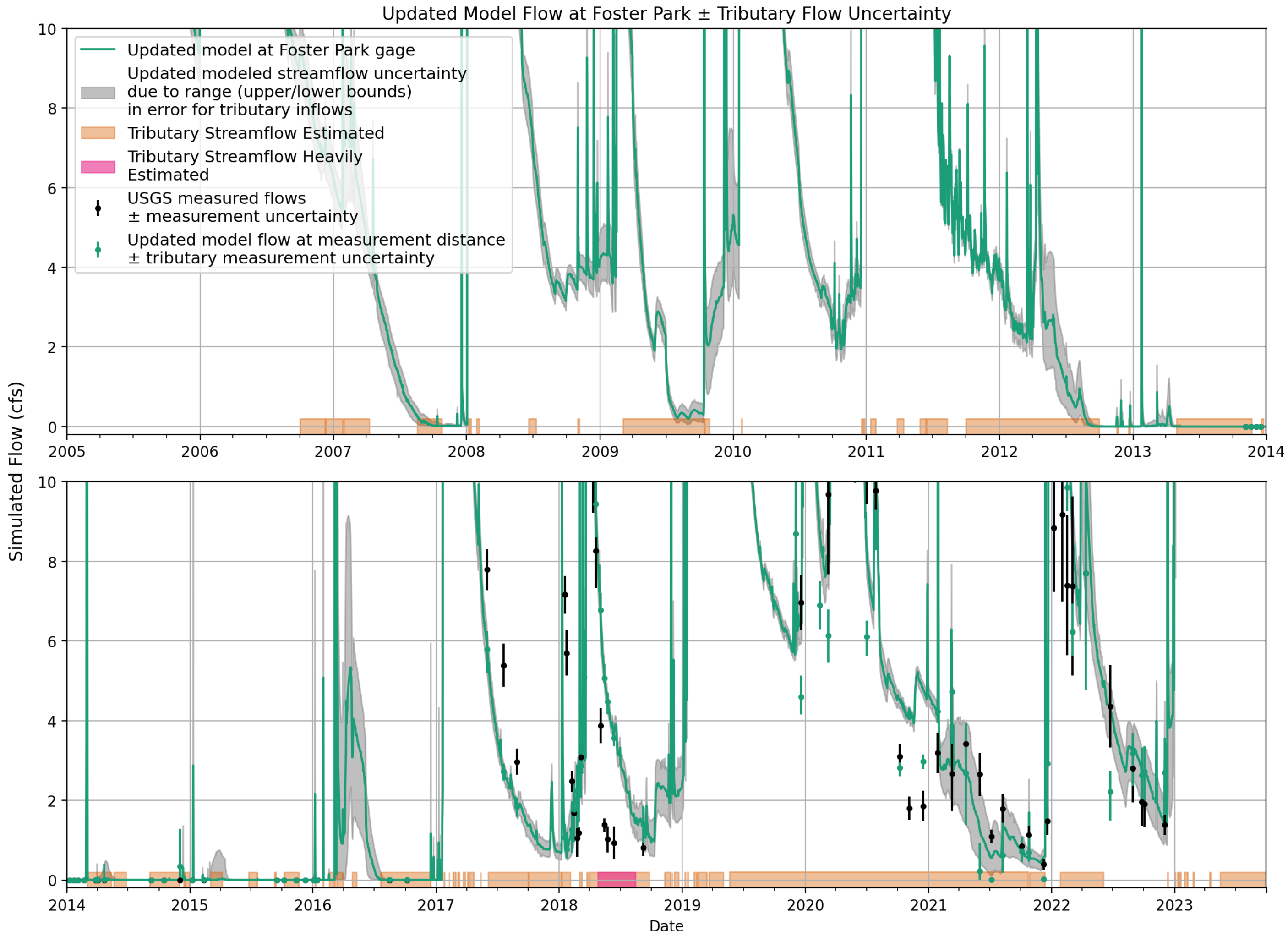
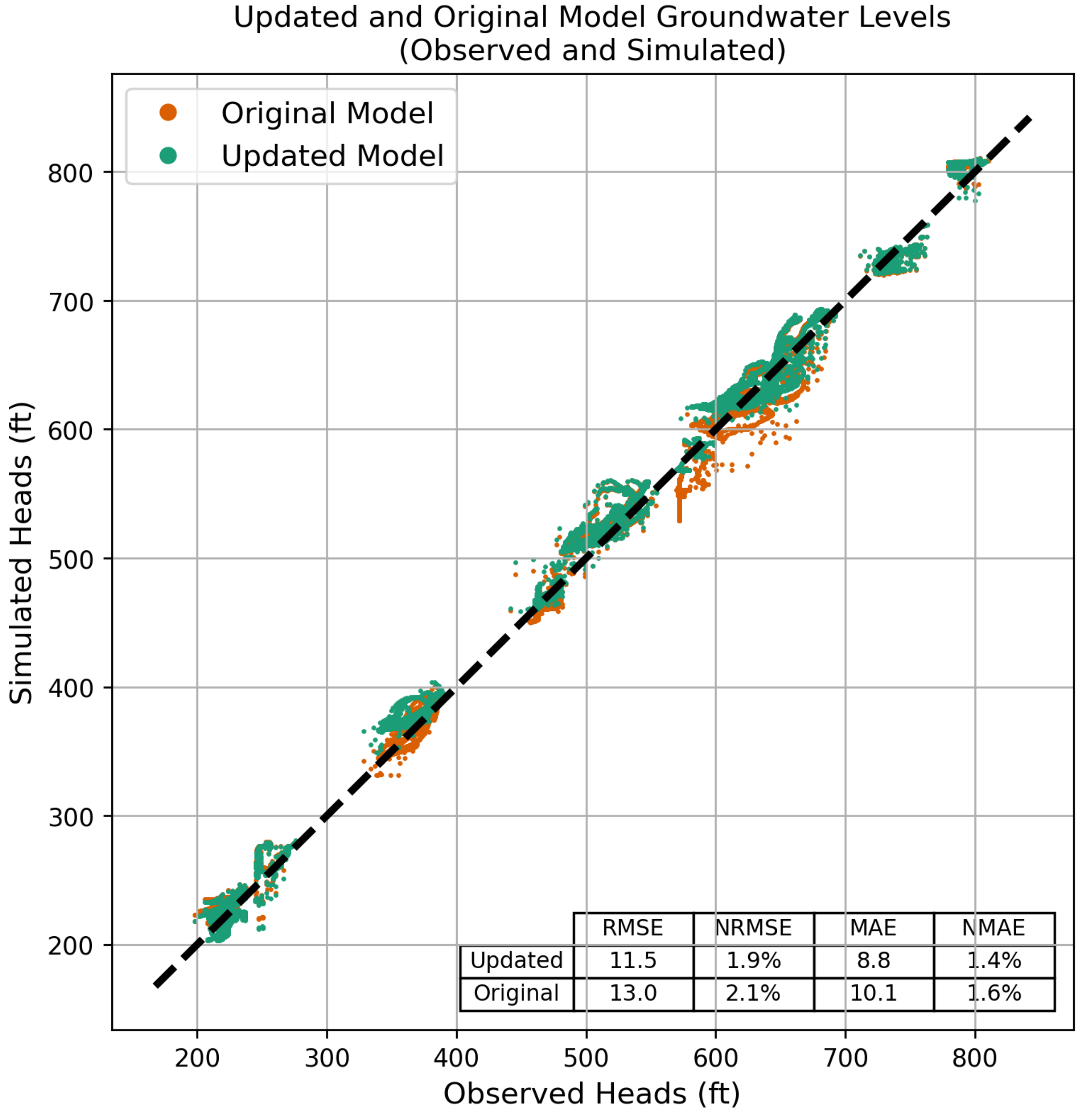


Figure 4-4. Updated model streamflow with applied range in error for tributary inflows (green line with transparent gray band [at Foster Park] and green dots with error bars [at measurement location]) versus observed streamflow (black dots with error bars [at measurement location]). Transparent orange bands along the x-axis show where at least one tributary is estimated, and red band (i.e., 2018) indicate extended (greater than 2 months) periods where more than one tributary gage is estimated.



	RMSE	NRMSE	MAE	NMAE
Updated	11.5	1.9%	8.8	1.4%
Original	13.0	2.1%	10.1	1.6%

Figure 4-5. Updated model simulated versus observed groundwater level data and objective function metrics. NRMSE and NMAE are the scaled RMSE and MAE, respectively (see Section 3.3.3).

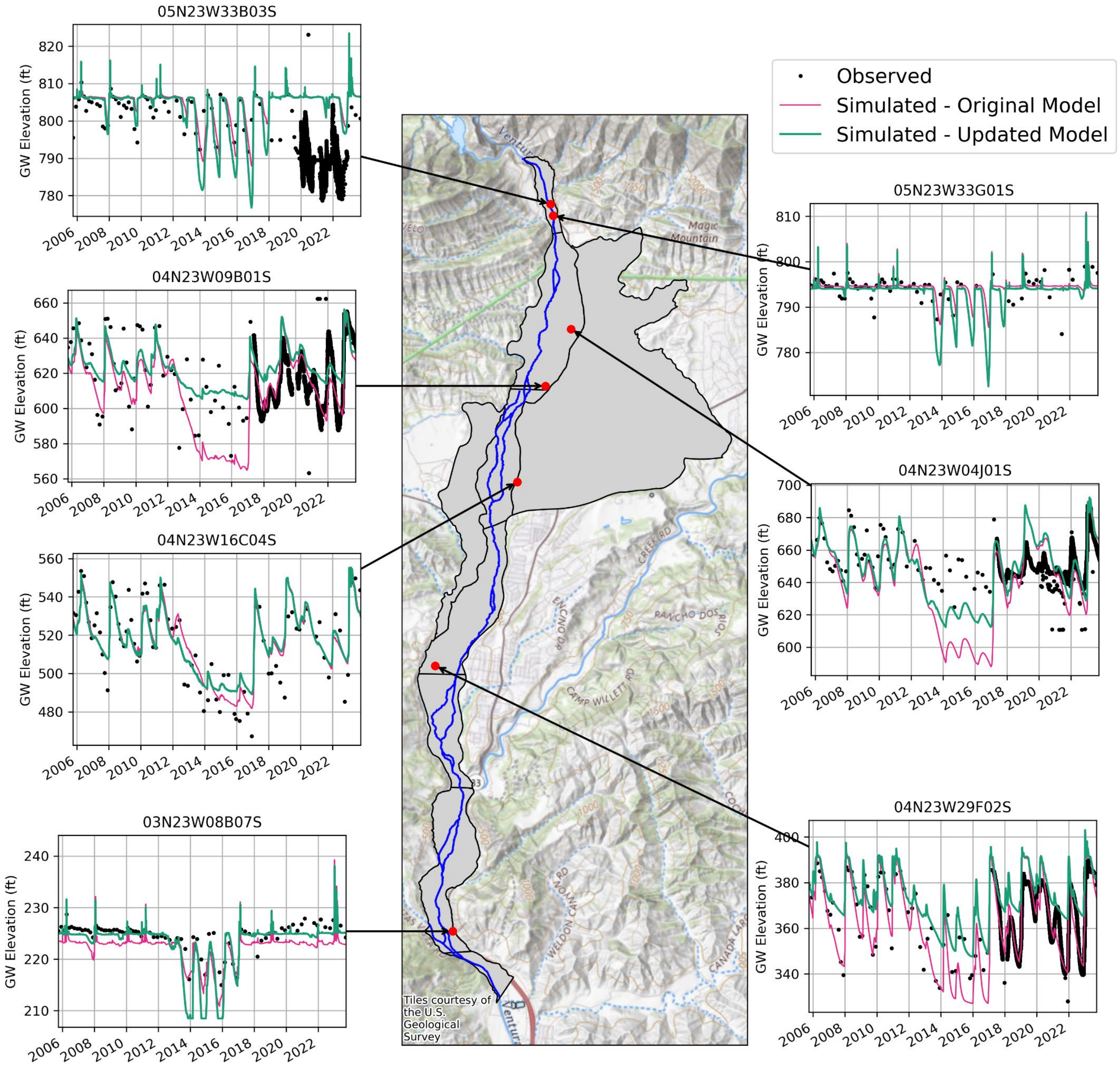


Figure 4-6. Key hydrographs for the original and updated model simulated and observed groundwater level data.

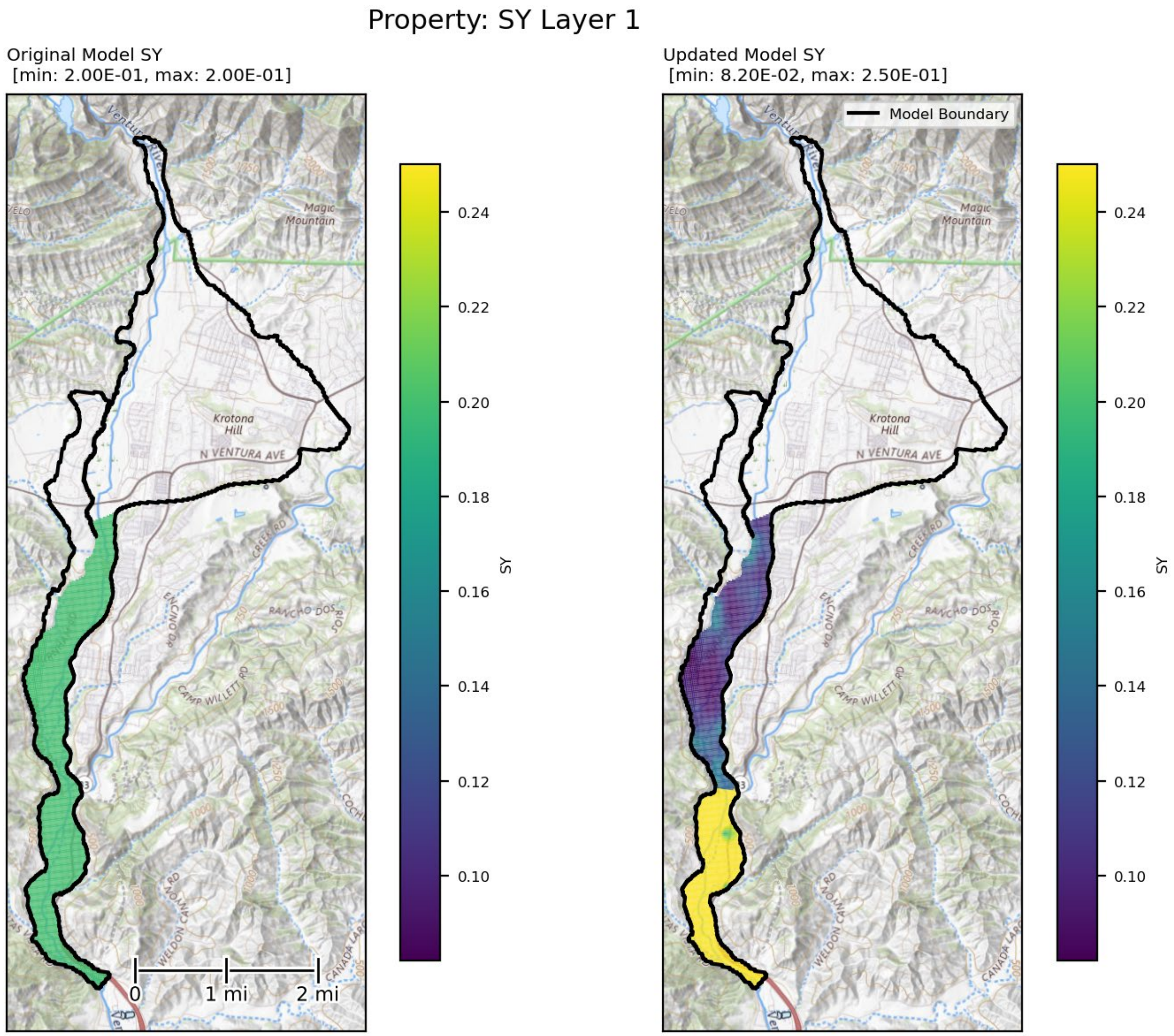


Figure 4-7. Mapped distribution for specific yield (Sy) in Layer 1 for the original model (left) and final updated model (right).

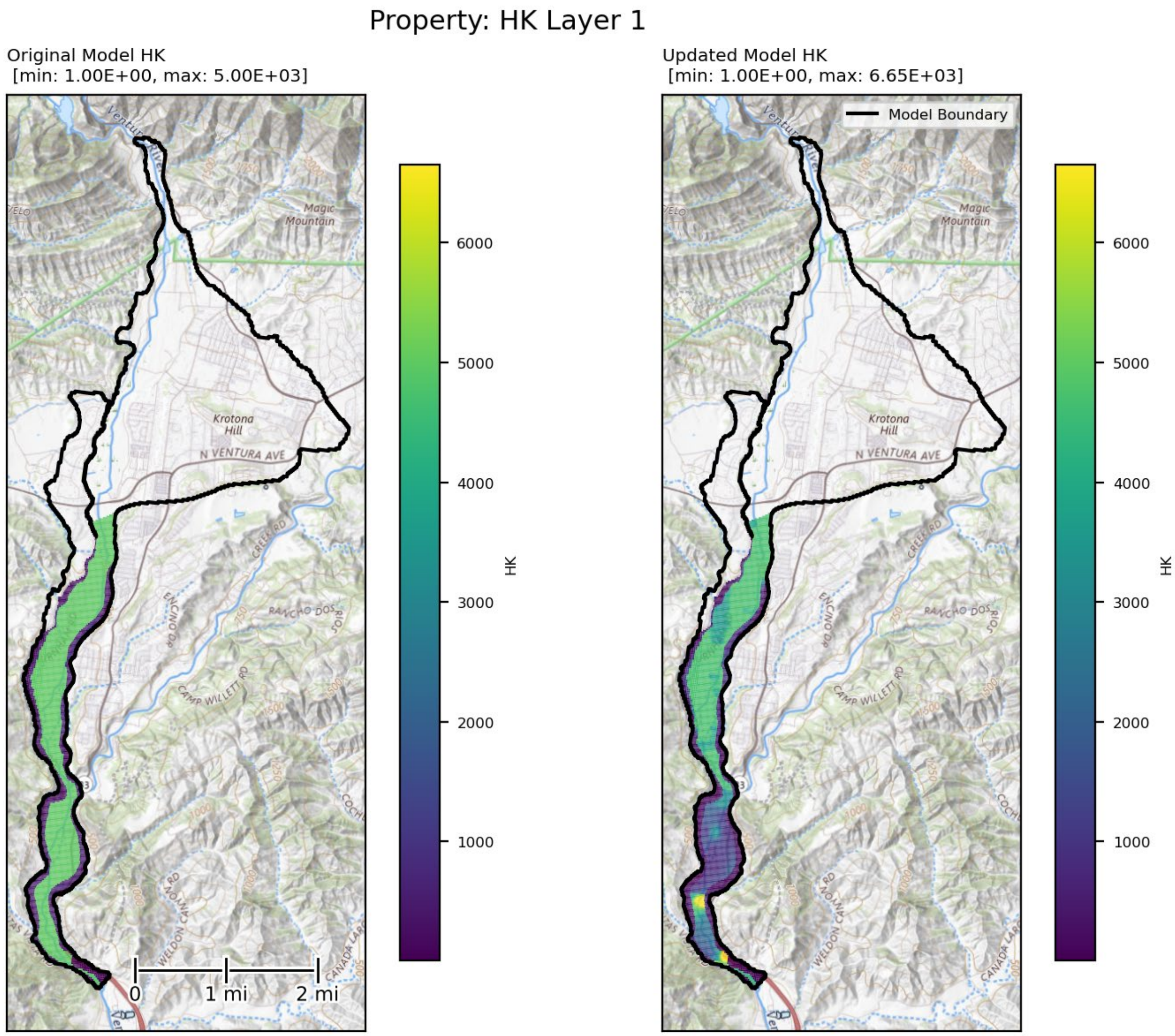


Figure 4-8. Mapped distribution for hydraulic conductivity (HK) in Layer 1 for the original model (left) and final updated model (right).