Solomon River Groundwater Models – Development and Application

S.S. PAPADOPULOS & ASSOCIATES, INC.
Environmental & Water-Resource Consultants

June 30, 2009

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Prepared for:

Kansas Water Office

Prepared by:

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REPORT

Section 1
Introduction

S.S. Papadopulos & Associates, Inc. (SSP&A) was contracted by the Kansas Water Office (KWO) to develop two independent groundwater models for the North and South Fork basins of the Solomon River in Kansas. The purpose of the model development is to provide a tool for simulating historical conditions in the alluvial aquifers, estimating water levels and water level changes in the aquifer, and analyzing alternative groundwater management scenarios.

The model development was based on information provided by the Kansas Water Office and other sources. The model was used to simulate historical aquifer conditions from 1948 to 2005. In addition, the model simulation timeframe was extended 50 years into the future to allow for the prediction of water level changes due to irrigation pumping and changes in hydrologic conditions, and the prediction of streamflow depletions to Solomon River.

The Solomon River North and South Fork basins share part of their domain with the existing regional RRCA (Republican River Compact Administration) Groundwater Model, developed by the States of Kansas, Nebraska, and Colorado. The regional model was recently refined, updated, and recalibrated by SSP&A in the area of northwest Kansas. The updated model was used for the calculation of appropriate boundary fluxes for the Solomon River models.

Section 2
Analysis

The development and calibration of the groundwater models for the unconfined alluvial aquifers in the Solomon River North and South Fork basins was based on compilation of a variety of geologic and hydrogeologic information. This information included data from a wide precipitation station network for the estimation of the areal recharge to the model, and detailed calculations of lateral boundary fluxes where the models shared parts of their domain with RRCA Groundwater Model.

After the model calibration process was completed, the calibrated model was used to evaluate alternative groundwater management scenarios in both basins. This task included developing a 50-year scenario of future hydrologic conditions that was representative of historical conditions that had been experienced and may occur in the future. Alternative groundwater management scenarios were then evaluated using the 50-year scenario of hydrologic conditions.

Model Development

Horizontal and Vertical Discretization

The first step in the model development process was to define the appropriate spatial extent for each model. Maps provided by KWO were used, depicting the main stem and tributaries of the North and South Fork and delineating the extent of the alluvial aquifer of interest. The resulting spatial extent of the two models is illustrated on Figure 1. The North Fork model includes the North Fork main stem and Bow Creek and encompasses an area of approximately 2,200 square miles. The South Fork model encompasses an area of approximately 1,200 square miles. A grid spacing of one-eighth mile in each direction was chosen for both models. This grid resolution was necessary to provide sufficient definition of geologic and hydrogeologic features within the model areas. The North Fork model grid consists of 224 rows and 640 columns. The South Fork model grid consists of 168 rows and 528 columns. The model active cells define the extent of the alluvial aquifer. However, in areas where the two models share parts of their domain with the RRCA Groundwater Model domain, the active cell grid was extended to encompass entire active cells of the RRCA model (Figure 2).

The geologic information available for the two basins was compiled and reviewed. Spatial data for the bedrock surface which represents the bottom of the model were interpolated using a kriging interpolation algorithm in order to develop a spatially distributed bottom elevation for the model. The formation thickness was then determined based on surface elevations obtained from Digital Elevation Model data available from the USGS.

River bottom elevation data, in the form of surveyed bottom elevation values, were linearly interpolated and combined with maps of the river extent in plan view to define the river geometry. The distribution of active cells in the model was determined by the delineated extent of the alluvial aquifer.

Time Discretization

The model simulates steady-state conditions in the aquifer representing the predevelopment period prior to 1948. Historical aquifer conditions are simulated for the period 1948 to 2005 with transient-state monthly stress periods. This time discretization is identical to that of the recalibrated RRCA Groundwater Model and was selected to enable communication between the local models and the RRCA model for the development of the local model boundary conditions as will be described in subsequent paragraphs.

Boundary Conditions

Historical pumping conditions in the North and South Fork basins were included in the model in the form of distributed pumping rates in corresponding model active cells encompassing actual points of use. Those pumping rates were provided by KWO and represent net irrigation and municipal/industrial pumping (i.e. considering groundwater return flows). The rates were calculated based on a combination of available water use report data and estimates based on irrigated acreage and crop demand for years prior to the availability of reliable water use reports.

In the areas where the local models share part of their domains with the RRCA Groundwater Model domain, a flux boundary condition was defined. The flux represents the simulated RRCA model flows across the corresponding local model boundary cell boundaries. To facilitate the detailed calculation of the distributed flux along the boundary, the local model grid was aligned with the RRCA model grid. The active local model grid was extended to encompass areas equivalent to the size of RRCA model cells thereby defining a zone of interaction between the two models (Figure 3). Groundwater flows along the lateral faces of the RRCA model cells immediately outside those cells falling within the local model domain, were calculated from the RRCA model results for the period 1947-2005. For each RRCA model cell, the corresponding lateral flows were then distributed to the eight local model cells along that face of the RRCA model cell as areal recharge. In addition, local model cells falling outside the originally defined extent of alluvium were assigned geometric and hydraulic conductivity properties reflecting those of the RRCA model cells they fell within. The property values in those cells was calculated in the form of a spatial distribution in order to maintain the spatial variability of those properties in the RRCA model and provide a smooth transition between the RRCA model and the local model.

Parameter Values

Initial hydraulic conductivity distribution in the models was based on preliminary estimates of aquifer transmissivity and similar properties in neighboring areas covered by the RRCA model. The final hydraulic conductivity distribution was determined during the model calibration process, as described later in this Report.

Calculation of the areal recharge was based on data from 31 precipitation stations which were used to estimate annual precipitation. Groundwater recharge was estimated in a manner similar to that used in the recalibration of the RRCA Groundwater Model using precipitation information and soil classification. A series of curves that relate annual precipitation to annual groundwater recharge for each soil class were used, defined by a continuous curve using a power function. The power function had the form: $R = A\,[(P - Po)^{n} - 1]$, where R is annual groundwater recharge, A is a coefficient, P is annual precipitation, Po is the value of annual precipitation where R equals zero, and n is a value that defines the shape of the curve. Values for the parameters a, Po and n were initially estimated and finally determined during the calibration process. The power function parameters that were ultimately used are shown on Table 1.

Evapotranspiration (ET) values were generated for the entire model area based on a procedure similar to that used for the RRCA model. Land coverage distributions provided by KWO were combined with measured ET data from McCook and Red Cloud climate stations. Based on monthly data, average yearly values of ET were calculated for those stations and simple linear interpolation in the x-direction was implemented for the calculation of ET values across the model domain.

Model Calibration

The calibration effort focused on the estimation of changes in groundwater levels and stream flows over time, and estimation of groundwater recharge associated with wet and dry periods. The combined manual and automated calibration process was facilitated by the use of PEST and post-processing tools developed by SSP&A.

Model calibration to transient response of water levels and stream flows to pumping and other stresses is important because the model will be used to evaluate the impact of future groundwater management scenarios on groundwater levels and stream flow. On the other hand, groundwater recharge and its contribution to the groundwater budget is an important consideration for the design and evaluation of groundwater management alternatives.

Model Calibration Data

Groundwater Levels

SSP&A was provided with a data base of groundwater level measurements for the North and South Fork basins. This data base contained almost 2,000 measurements of groundwater levels from 36 wells within the two basins, with data extending from 1947 to 2005 for the North Fork and 1952 to 2005 for the South Fork (Figure 4 and Figure 5, respectively). SSP&A organized the data into various worksheets and files for use in the calibration process. The model calibration was based on the direct comparison of measured groundwater elevation data to model results corresponding to the location and time of each measurement. Various qualitative metrics such as the cumulative frequency of the groundwater level residuals (that is, the difference between measured and calculated groundwater levels) were used to evaluate the model calibration. Comparisons were made both statistically and graphically to aid in adjusting model parameters and conditions during the calibration process.

Stream Flows

Stream flow data were also used as calibration targets in this study. Baseflow (the contribution of groundwater to the total stream flow) was the specific calibration target. Baseflow estimates derived from stream flow measurements at gaging stations on the North Fork of the Solomon River, on Bow Creek, and on the South Fork of the Solomon River were obtained from KWO and were compared to model results. During the calibration process, model results in terms of baseflow were reviewed and model parameter were adjusted accordingly.

Model Calibration Calculations

Groundwater Recharge

As described earlier, groundwater recharge was estimated using a series of curves that relate annual precipitation to annual groundwater recharge based on soil classification. During the calibration process terrain multipliers were used to provide for adjustments to the recharge curves in certain geographic areas. These adjustments were in the form of a scalar multiplier that was applied to the groundwater recharge obtained from the recharge curves (Figure 6). Multipliers were specified at various points throughout the model domain and values at individual model cells were obtained by applying a kriging algorithm to determine specific values at model node points. This approach allowed for both a temporal and spatial scaling of the values for groundwater recharge obtained from the recharge curves. Through this adjustment, a different set of terrain multipliers could be specified from one year to the next. This modification provided a mechanism for adjusting groundwater recharge during exceptionally wet or dry years and for specifying a geographic distribution to the adjustments. The geographic patterns and amounts of adjustment for different years were determined as part of the calibration process.

During the calibration process, the terrain multipliers were adjusted to try to improve model results, especially in terms of changes in computed groundwater levels over different time periods. The goal of the adjustments was to refine estimates of groundwater recharge from year to year. The adjustments were based on a comparison of the changes in groundwater levels that were observed over different time periods to computed changes over the same periods. The refined set of annual recharge values would ultimately be used to evaluate potential future scenarios of groundwater pumping from the groundwater management district.

Hydraulic Conductivity

The hydraulic conductivity distribution was also adjusted during the calibration process. Hydraulic conductivity values were specified at various points within the model domain and were distributed to the entire model domain using a kriging algorithm. The various point values were then determined during the calibration process using automated parameter estimation method and professional judgment, and updated distributions were developed for the entire model.

Model Calibration Results

Groundwater Level Hydrographs

The data on groundwater levels provided to SSP&A contained measurements from 46 wells located within the model domains of the North and South Fork models. There were 30 observation wells within the North Fork model domain and 16 wells within the South Fork model domain. The data from each of these wells were compared to model results at the corresponding location and time of each measurement.

The calibration statistics demonstrate a good model calibration to groundwater levels for both models. For the North Fork model the correlation coefficient, which expresses the one to one relationship between computed and measured water levels, was 0.99985. The average residual (difference between computed and measured values) for the 1,382 measurements was -0.86 feet. The median residual was 0.24 feet. The corresponding statistics for the South Fork model were 0.99989 for the correlation coefficient, -0.72 feet for the average residual, and 0.03 feet for the median residual of the 589 measurements.

The standard deviation (or sometimes termed the standard error) of the 1,382 residuals for the North Fork model was 5.33 feet. The values of measured water levels range from about 1,730 feet to 2,670 feet, a range of about 940 feet. The ratio of the standard deviation of the residuals to the range of the measured values is about one-half of one percent. In the South Fork the standard deviation of the 589 residuals was 3.83 feet. The values of measured water levels range from about 1,935 feet to 2,685 feet, a range of about 750 feet. The ratio of the standard deviation of the residuals to the range of the measured values is also about one-half of one percent. Values of this ratio below ten percent are generally considered satisfactory, suggesting that the calibration that was achieved for the two models is more than satisfactory.

Another objective in the model calibration process is to avoid residuals that are predominately positive or negative in a geographic area or over different time periods. Figure 7 and Figure 8 show the cumulative frequency diagrams of the residuals for North and South Fork models, respectively. These charts summarize the distribution of residuals. Although the average residuals have a slightly negative bias in both cases, the median residual is almost zero in both cases. The slightly negative bias could be attributed to a limited number of larger residuals that skew the computed average residual to some degree.

Scatter diagrams for the calibrated North and South Fork models are shown on Figure 9 and Figure 10 respectively. The overall correspondence between the computed and measured values is very good. This observation is consistent with the correlation statistics referred to previously where a value of the correlation coefficient of 1.0 would indicate perfect correlation.

While the scatter diagram provides one measure of model calibration, the wide range in measured values of groundwater level elevation (from about 1,700 feet to 2,700 feet) can obscure the correspondence between values over time at individual well locations. Also, calibrating only to groundwater level elevations when the range in elevations is large can reduce the sensitivity of the process to changes in groundwater levels over time at individual well locations.

Stream Flows

Model calibration to stream flow data was performed qualitatively. Model parameters were adjusted so that the contribution of groundwater to stream flow would reasonably match the estimated baseflow. Figure 11 and Figure 12 illustrate the model calculated baseflow at the two gaging stations on the North Fork and Bow Creek and how they compare to the estimated baseflow at those gages. Figure 13 illustrates a similar comparison for the South Fork.

In both cases, the calibrated model results are in reasonable agreement with the estimated values. The model reasonably reproduces the baseflows during both wet and dry periods, suggesting that groundwater recharge in the model has been adequately quantified.

Alternative Groundwater Management Scenarios

Several alternative future groundwater management scenarios were analyzed. Each analysis evaluated conditions for a period of 50 years into the future. The calibrated model was used to simulate these scenarios and groundwater budgets were compiled for each scenario. The predictive simulations were based on a representative 50-year sequence of hydrologic conditions (groundwater recharge and pumping) that was developed for the purposes of this analysis. The development of this 50-year sequence is discussed in following paragraphs.

The alternative groundwater management scenarios considered as part of this study were the following:

- Status Quo: pumping conditions during 2005 held constant for the 50-year period.
- Only Alluvial Pumping: future pumping limited to pumping conditions during 2005 from irrigation wells extracting water solely from the alluvium.
- Only Ogallala Pumping: future pumping limited to pumping conditions during 2005 from irrigation extracting water solely from the part of the Ogallala aquifer within the model domain.
- No Pumping: stop all irrigation pumping for the 50-year period.
- Lower ET: use a reduced potential evapotranspiration equivalent to 50% of the original potential ET for the 50-year period.
- No Marginal Soil Pumping: wells falling within areas representing marginal soils, as described in land coverages provided by KWO, were not pumped for the 50-year period.
- No Anomalously High Precipitation: a modified 50-year sequence of hydrologic conditions was developed in which years of anomalously high precipitation were substituted by the median precipitation from the original sequence.

Representative 50-year Hydrologic Sequence

A representative 50-year sequence of hydrologic conditions was developed to provide for an evaluation of alternative groundwater management scenarios. Simply assuming average conditions for the foreseeable future provides some measure of future expectation but will not reflect variations over dry and wet hydrologic cycles. In order to provide some level of hydrologic variation to the evaluation, a simple process was used to develop a variable and representative sequence of future hydrologic conditions.

The annual groundwater model recharge values for the historical period from 1970 to 2005 are shown on Figure 14 and Figure 15 for the North and South Fork model respectively. The future sequence was developed from these values in several steps. First, a cumulative frequency distribution of the estimated groundwater recharge in the North and South Fork model areas from the calibrated groundwater model for the 35-year period from 1970 to 2005 was prepared. Next, a pseudo 50-year cumulative frequency distribution was constructed using annual recharge values from the same period that had a shape that was approximately equivalent to the actual 35-year distribution for the period from 1970 to 2005. The years from 1970 to 2005 were selected because data from those years were considered to be more representative of current conditions with regard to groundwater pumping and irrigated acreage.

The pseudo 50-year distribution was then used to construct random 50-year sequences of groundwater recharge for the two basins. Fifty values were randomly drawn from the pseudo 50-year distribution over and over again. Each random 50-year sequence was then evaluated qualitatively and quantitatively. One of these sequences was then selected that had characteristics that would allow for a reasonable evaluation of future groundwater management scenarios. One desired characteristic was that the sequence had to have an average annual groundwater recharge that was similar to the longer-term average recharge obtained from the calibrated models. Another desired characteristic was that the sequence had consecutive years of both wet and dry hydrologic conditions within the sequence. The selected 50-year hydrologic sequences of groundwater recharge and the corresponding annual groundwater recharge for the North and South Fork models are shown on Figure 16 and Figure 17, respectively. In the case when no anomalously high precipitation years were considered, the corresponding 50-year sequences and annual groundwater recharge values for the North and South Fork models are shown on Figure 18 and Figure 19, respectively.

The 50-year sequences were also used for the assembly of the ET input to the model. The original model files were disassembled to annual datasets and then recompiled to reflect the 50-year sequence developed for the groundwater recharge.

Boundary flows for the predictive model were assumed to follow a pattern similar to that demonstrated in the historical model. Those patterns were evaluated separately for the North and South Fork models based on the corresponding datasets and the development of an exponential trend function. For the North Fork model the declining pattern was calculated using a trend function based on boundary flow values for the period 1967 to 2005, during which flow was following a monotonically decreasing pattern. The trend function had the form: $T = A\ e^{-bx}$, where A and b are coefficients, and x is the year. The trend function was then used for estimation of the annual boundary flow for the 50-year sequence (Figure 20). The annual boundary flow for the 50-year sequence for the South Fork was calculated in a similar manner, based on boundary flow values for from the period 2000 to 2005, to reflect the long-term declining pattern rather than short-term anomalous patterns that occurred during the late 1990s (Figure 21).

Results for Alternative Scenarios

Groundwater Level Decline

Estimates of the spatial distribution of projected groundwater level decline during the 50-year future hydrologic sequence ware calculated for each scenario. Results for the North Fork model are included in Figures 22 through 28. Figure 29 illustrates the difference in water level decline between the Status Quo and No Pumping scenarios. Similar results for the South Fork model are included in Figures 36 though 43.

Water Budget Tabulations

Groundwater budgets for each of the scenarios were compiled to characterize the relationship between recharge, storage depletion and groundwater inflow in response to pumping. Table 2 shows the groundwater budget summary for North Fork and Table 4 shows a similar budget summary for South Fork. The values shown on Tables 2 and 4 are average annual amounts over the 50-year future hydrologic sequence.

Stream Flow Tabulations

Figure 30 shows the historical baseflow and future baseflow under all scenarios for North Fork only, as calculated by the model. A depiction of only the future baseflow under all scenarios is included in Figure 31. A depiction of the difference in baseflow for North Fork under each scenario from the Status Quo scenario is shown in Figure 32. Similar results for Bow Creek are included in Figures 33, 34, and 35. Table 3 shows the baseflow summary for all scenarios for the North Fork model.

Figure 44 shows the historical baseflow and future baseflow under all scenarios for South Fork model. A depiction of only the future baseflow for each future scenario is included in Figure 45. A depiction of the difference in baseflow for South Fork under each scenario from the Status Quo scenario is shown in Figure 46. Table 5 shows the baseflow summary for all scenarios for the South Fork model.

Section 3
Conclusions

Groundwater models of the North and South Fork basins of the Solomon River in Kansas have been developed and calibrated to historical groundwater levels and stream baseflows. These models provide quantifications of historical groundwater recharge that represent the magnitude and variation in groundwater supply that occurred in the past and that can be expected to occur in the future. These quantifications also provide a basis for evaluating the impact of alternate future groundwater management scenarios on groundwater levels and stream flows. The evaluation of six alternate future groundwater management scenarios illustrated several important conclusions regarding future groundwater conditions in the basins.

1. Groundwater levels in the alluvial aquifers in areas where baseflow is sustained (eastern parts of the model areas) are not significantly affected by variations in assumed future pumping conditions.

2. Groundwater levels in areas where baseflows are not sustained are projected to decline significantly in the future, primarily as a result of continued groundwater storage depletion associated with regional groundwater pumping.

3. The impact of future alluvial pumping and Ogallala pumping within the model domains is to reduce baseflow and increase groundwater storage depletion in approximately equal proportions.

4. Potential ET salvage associated with future pumping is relatively small.

5. The impact of reducing future evapotranspiration is to increase baseflow by almost equal amounts.

6. Years of anomalously high precipitation provide a significant increase in groundwater recharge and groundwater supply; although the effect tends to dissipate within a few years.

7. Eliminating pumping in areas of marginal soils has a small impact on future groundwater levels and baseflows.

FIGURES

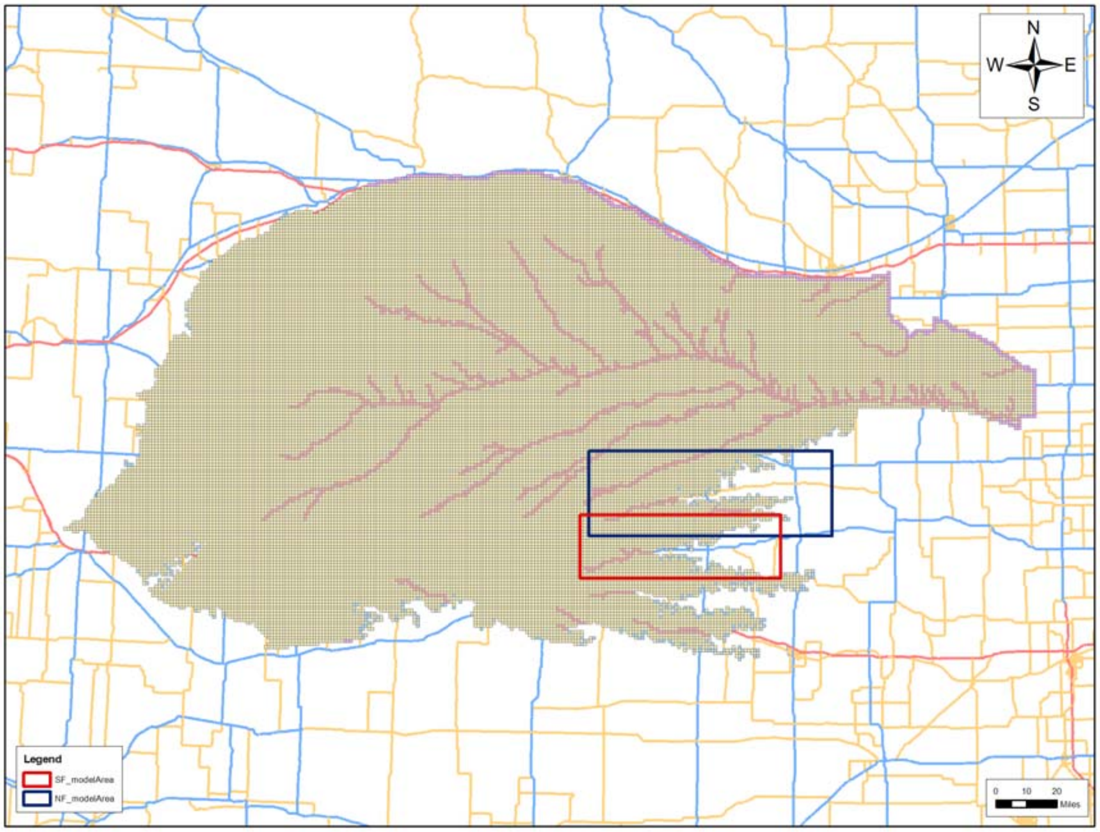


Figure 1 Solomon River Model Domain Outlines

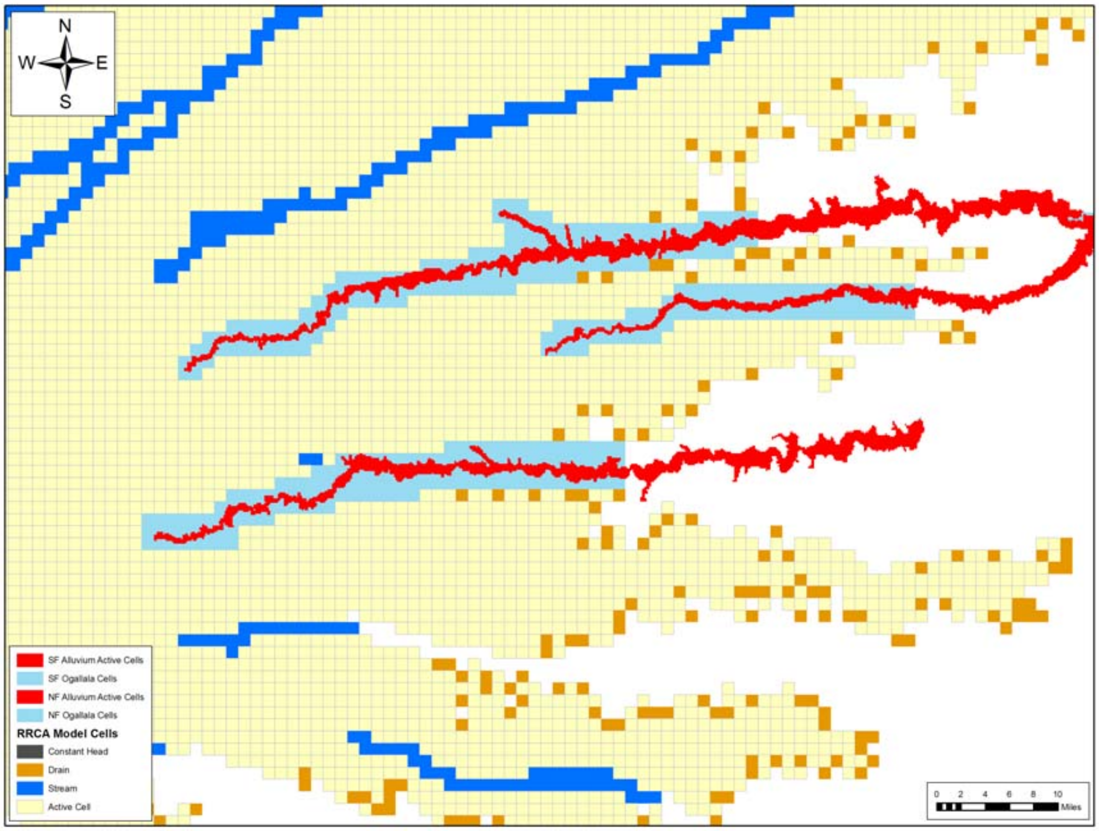


Figure 2 **Solomon River vs RRCA Active Cells**

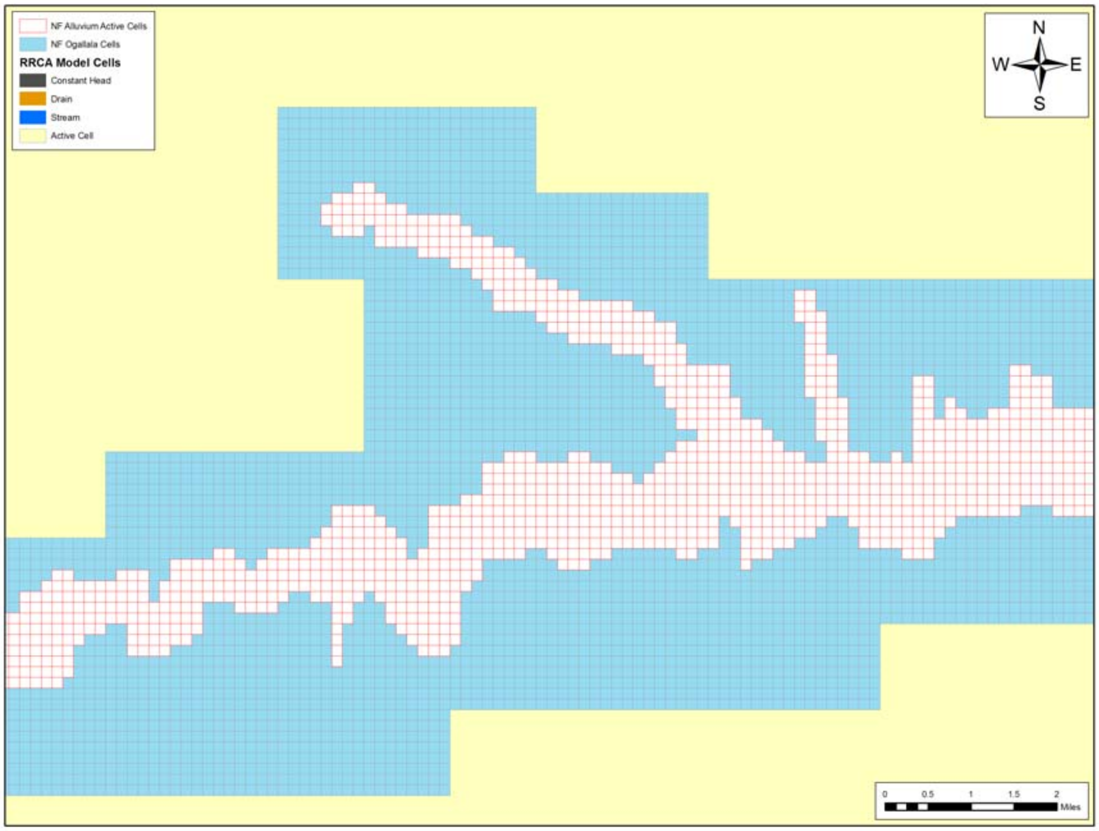


Figure 3 Solomon River Active Cells (detail)

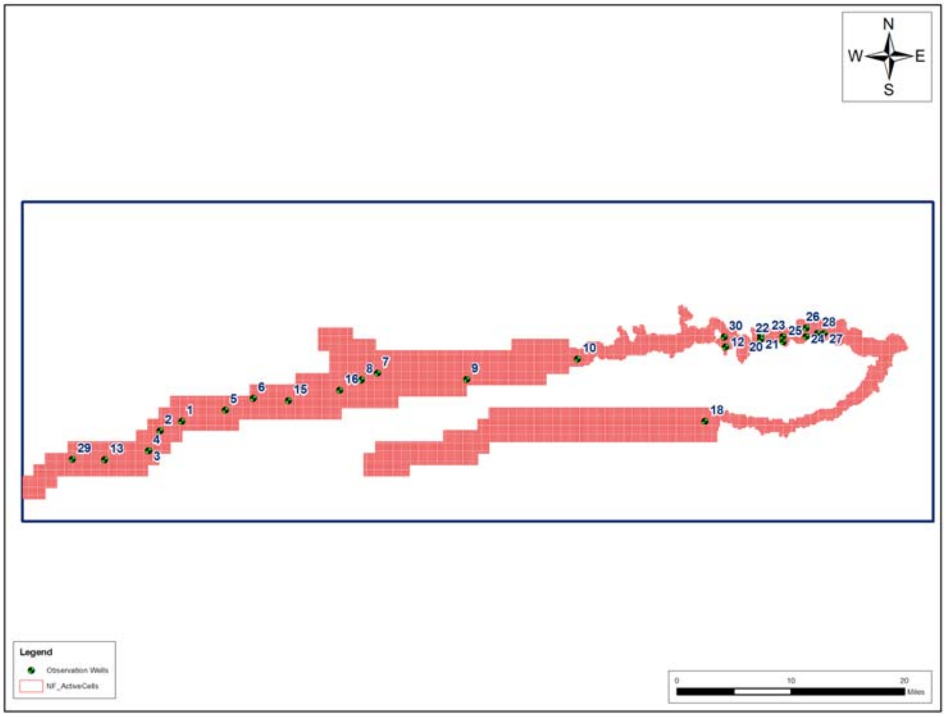


Figure 4 North Fork Model — Observation Wells

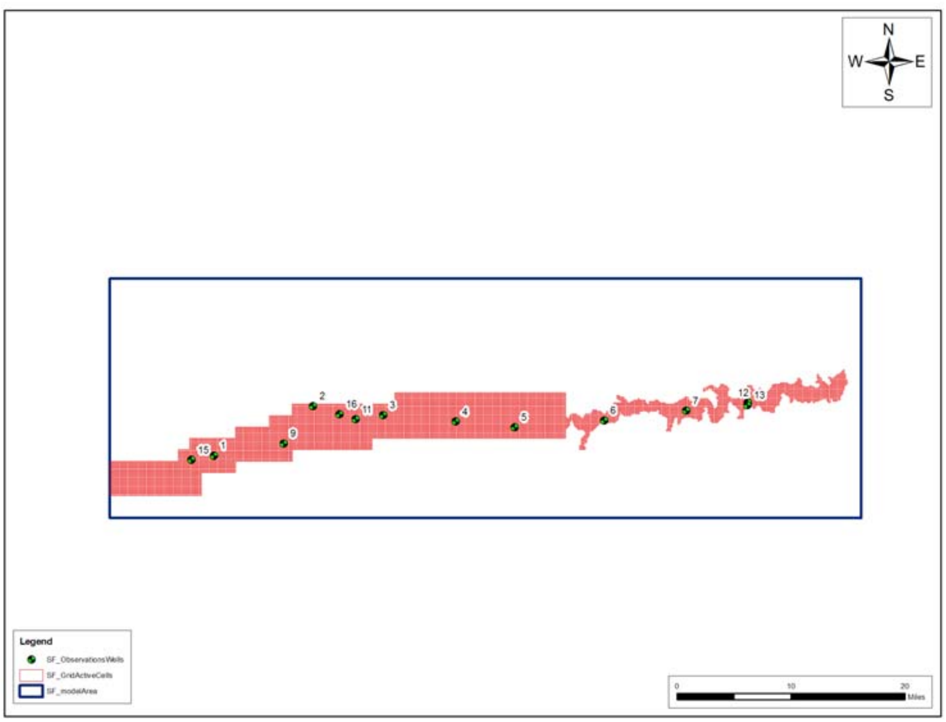


Figure 5 South Fork Model — Observation Wells

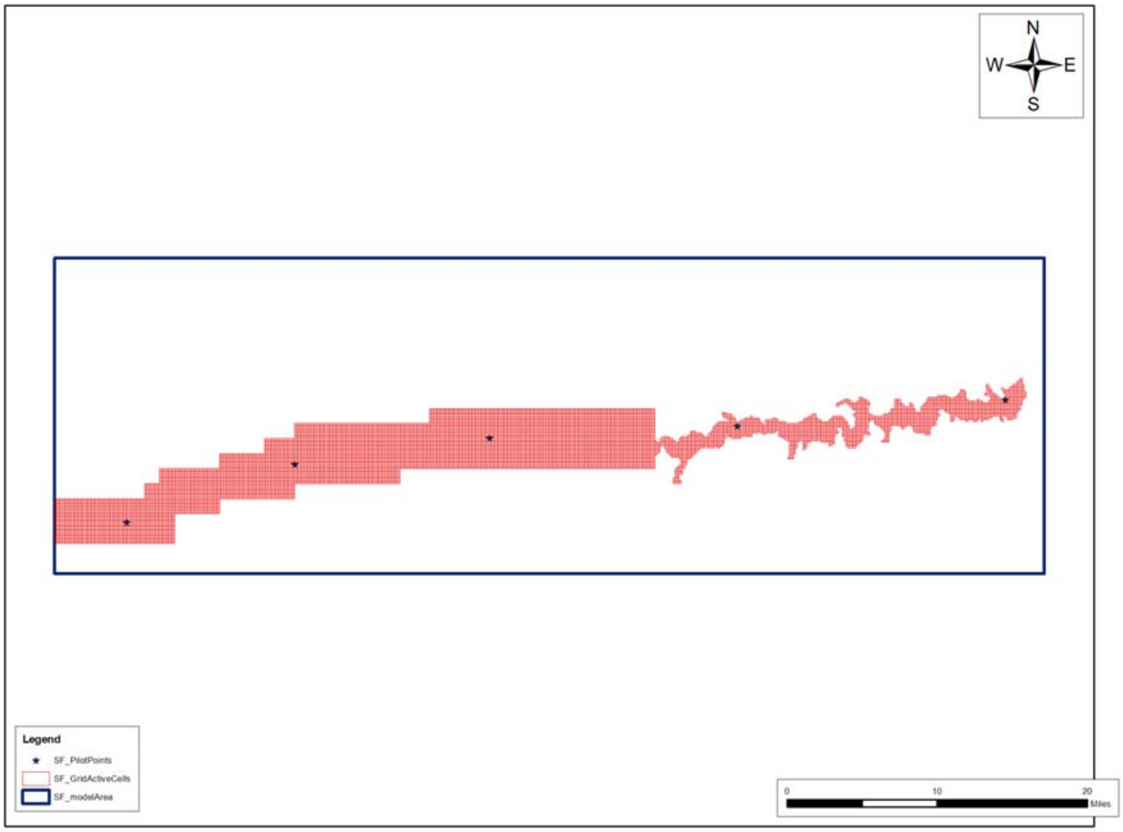


Figure 6 Terrain Multipliers

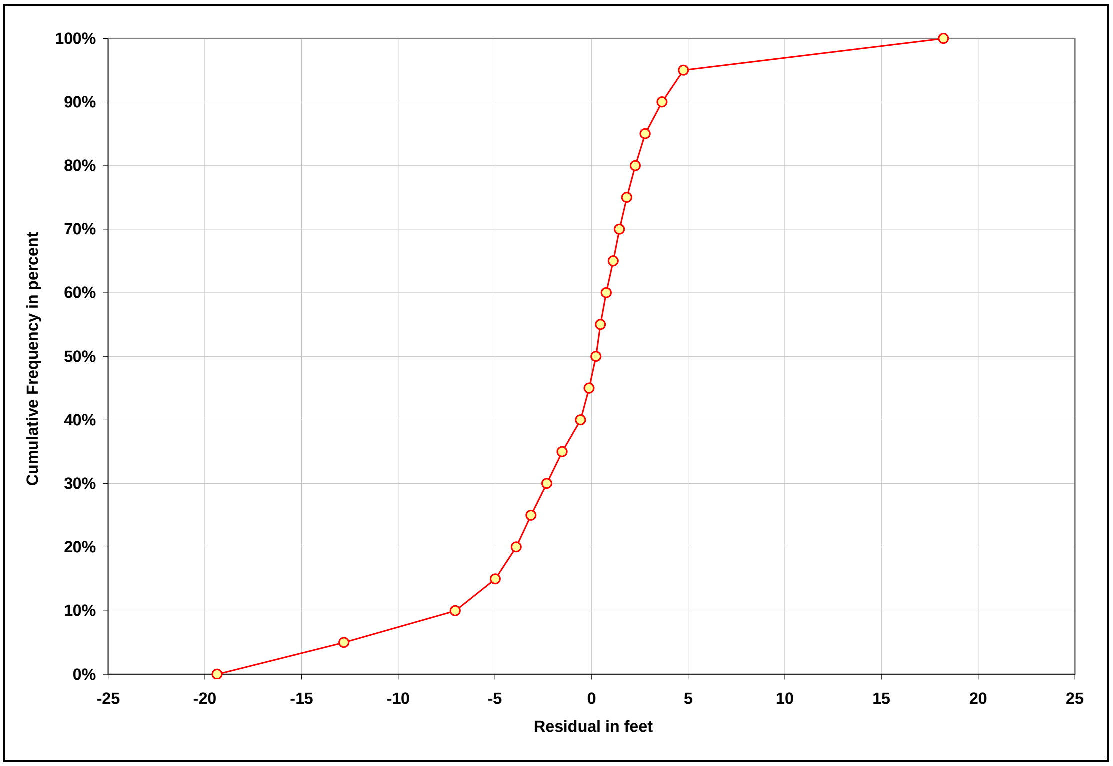


Figure 7 Cumulative Frequency of Residuals – North Fork

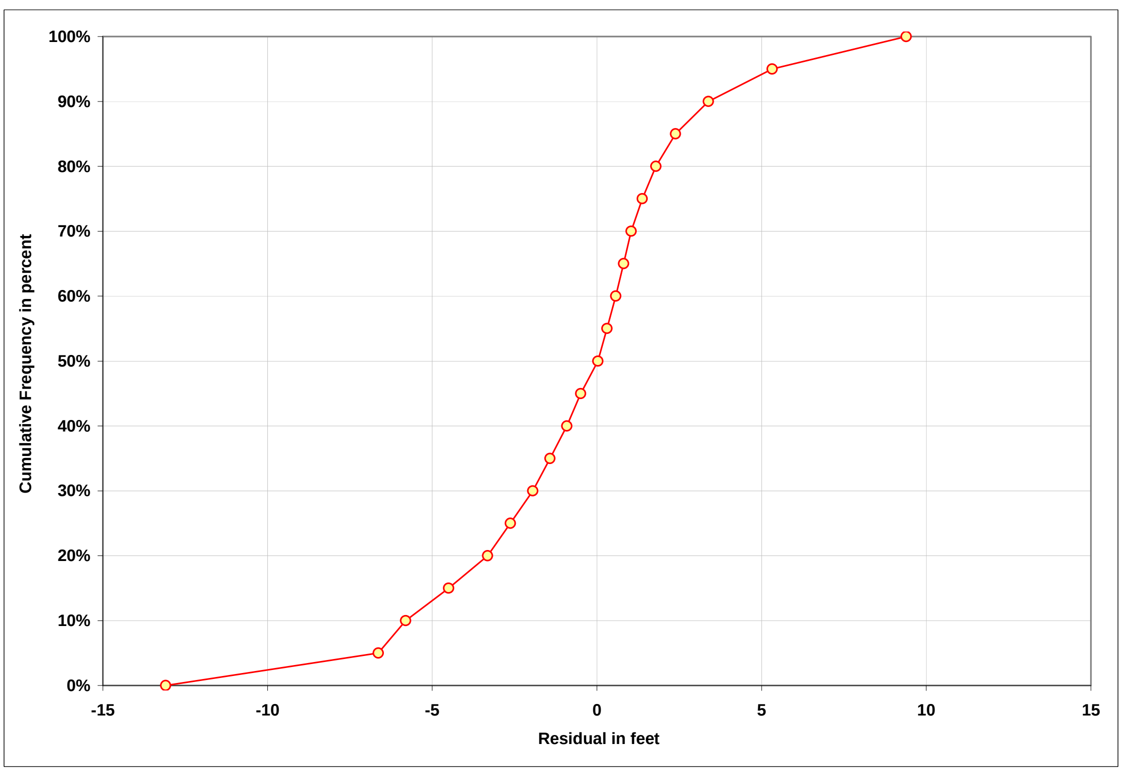


Figure 8 Cumulative Frequency of Residuals — South Fork

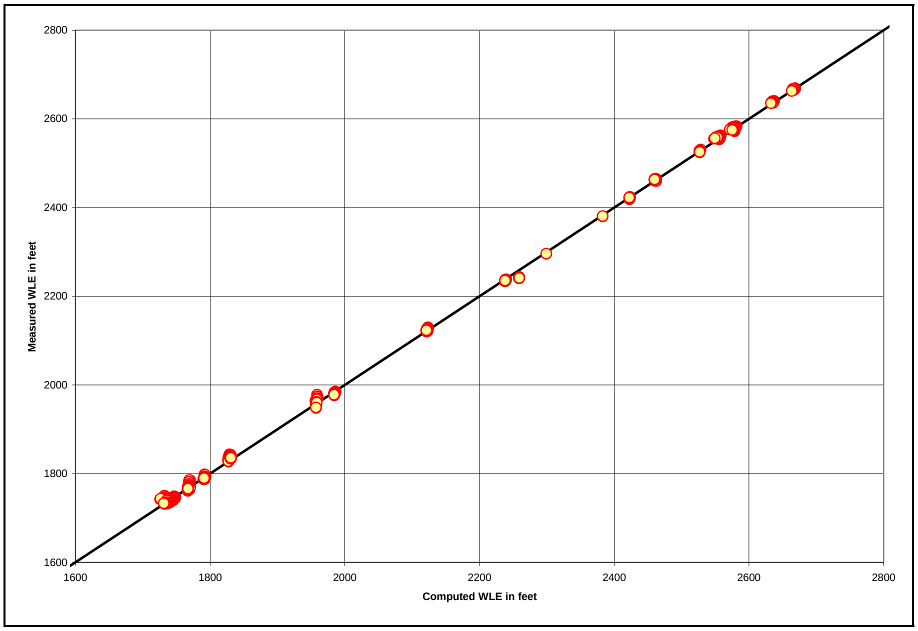


Figure 9 Scatter Diagram of Computed versus Measured Water Elevation – North Fork

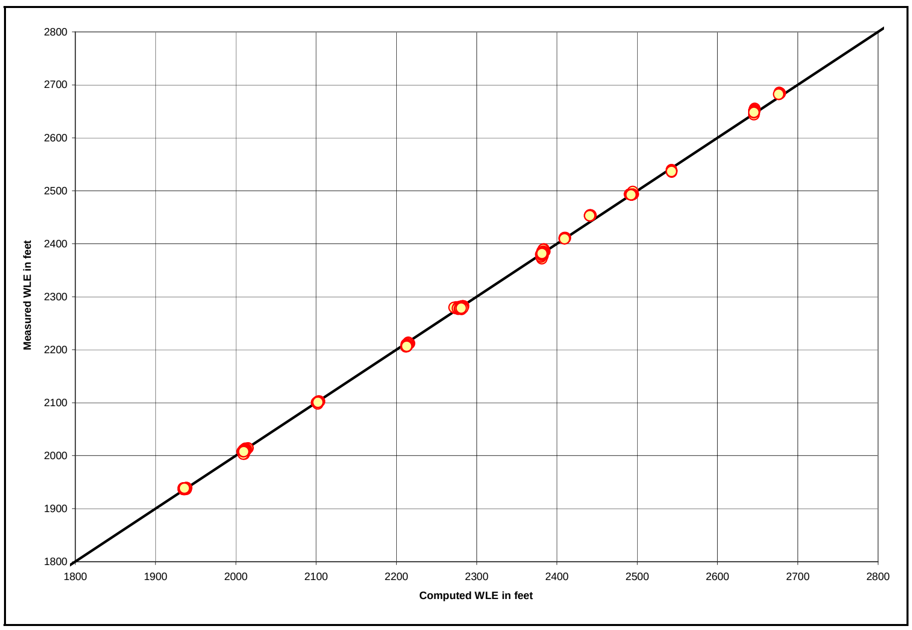


Figure 10 Scatter Diagram of Computed versus Measured Water Elevation – South Fork

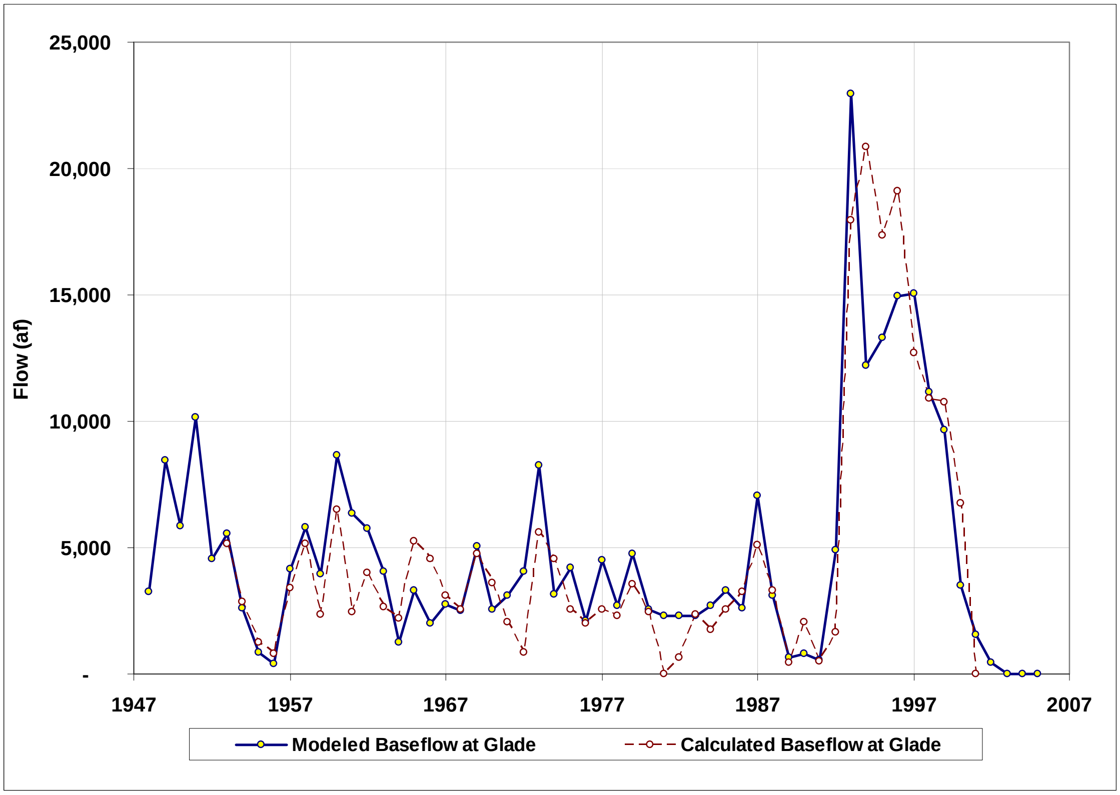


Figure 11 **Modeled and Calculated Baseflow at Glade — North Fork**

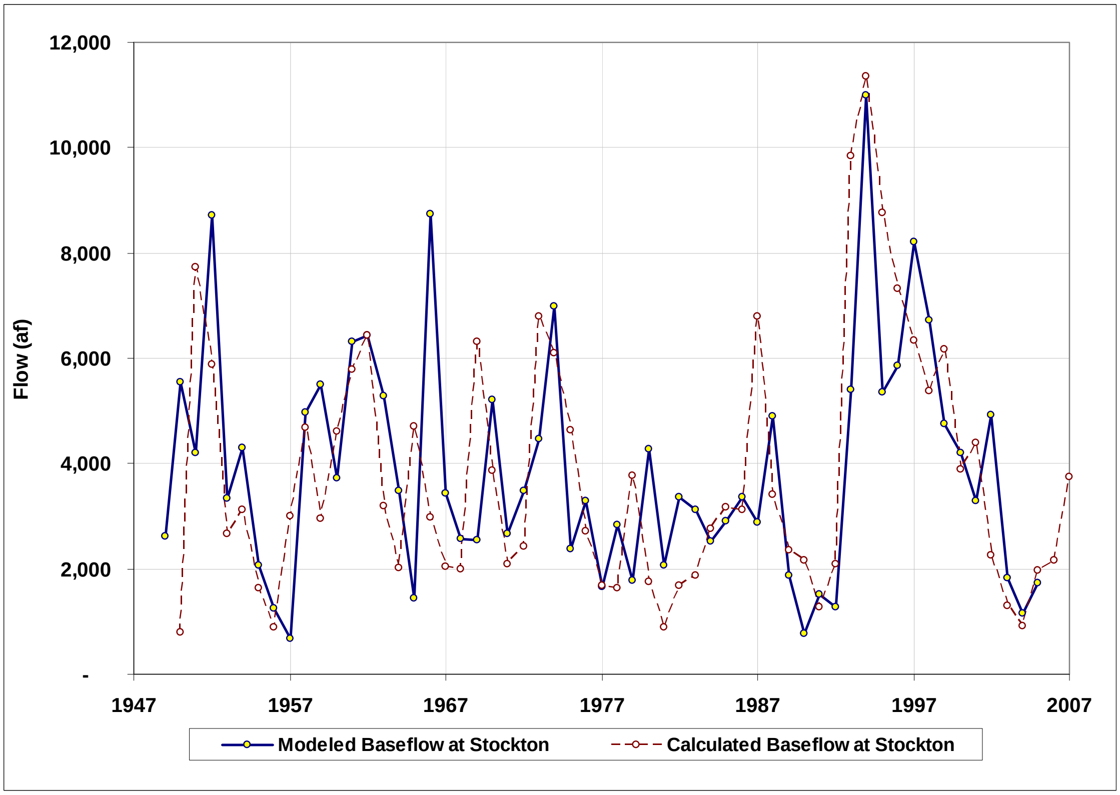


Figure 12 **Modeled and Calculated Baseflow at Stockton — Bow Creek**

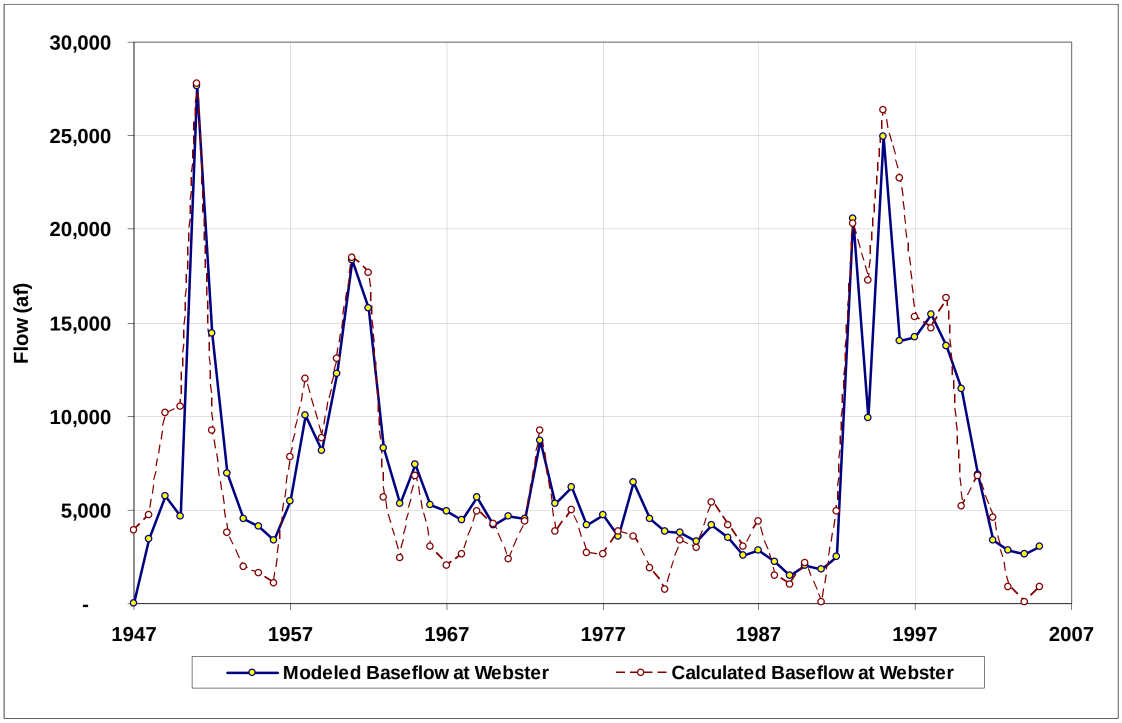


Figure 13 **Modeled and Calculated Baseflow at Webster — South Fork**

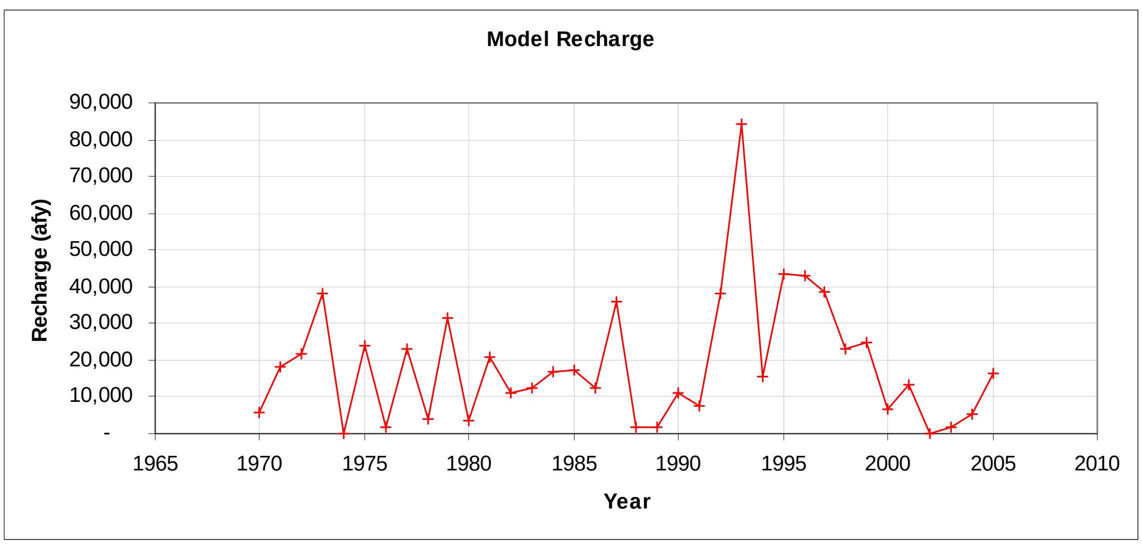


Figure 14 **Historical Model Recharge for the Period 1970-2005 North Fork**

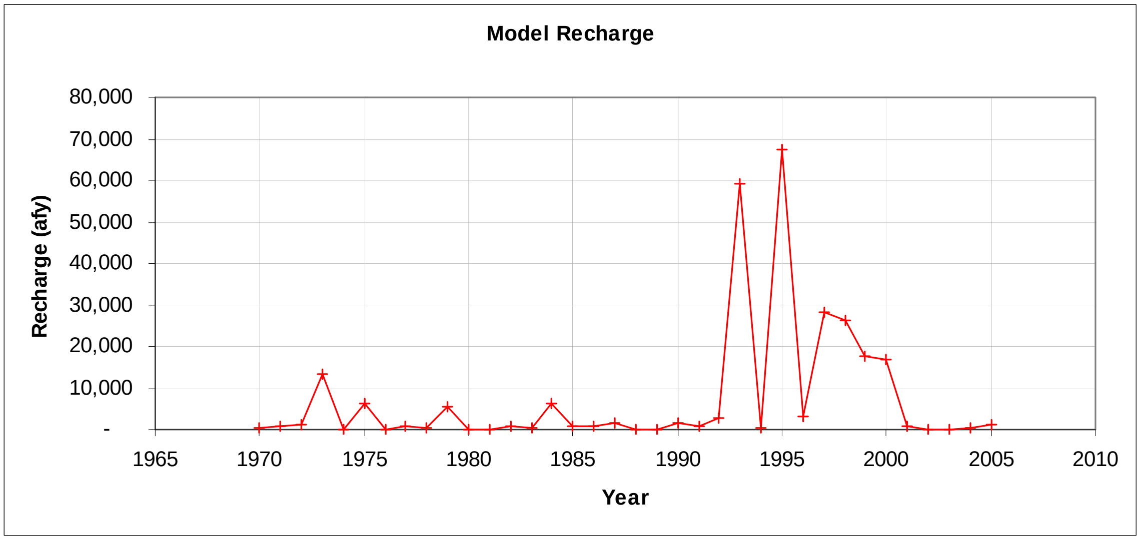
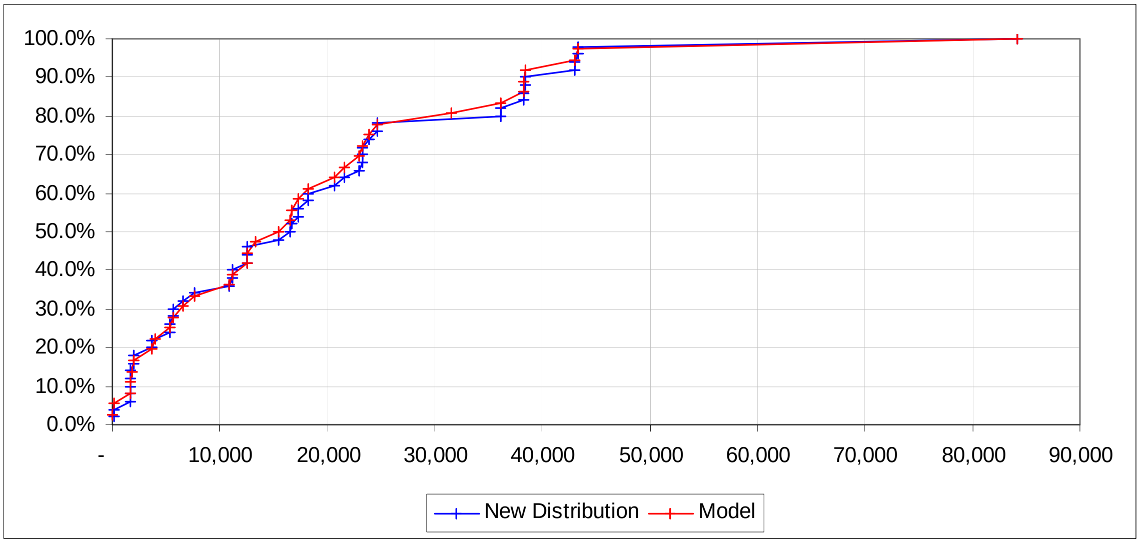


Figure 15 **Historical Model Recharge for the Period 1970-2005 South Fork**



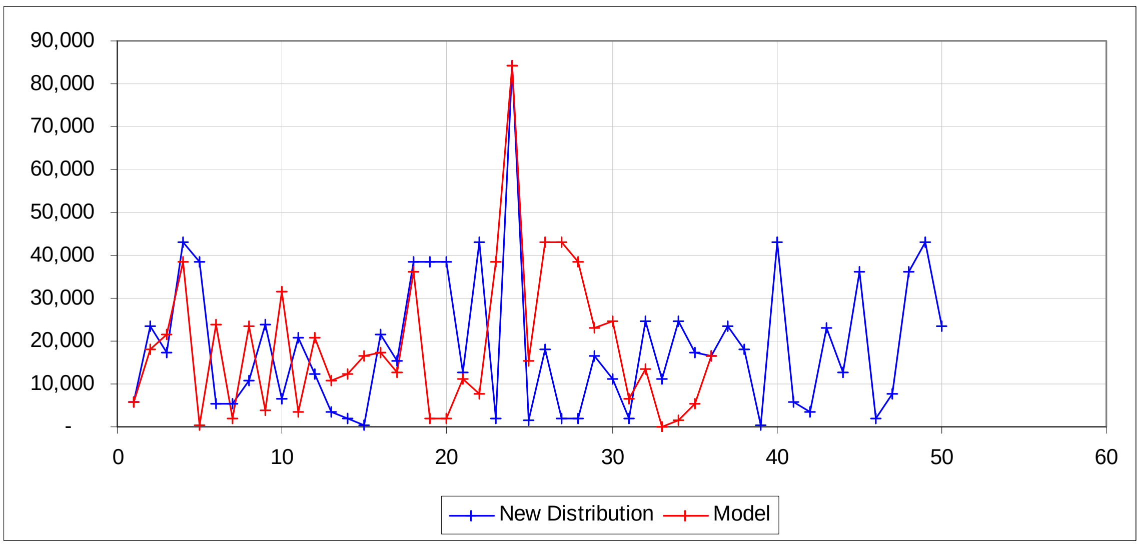
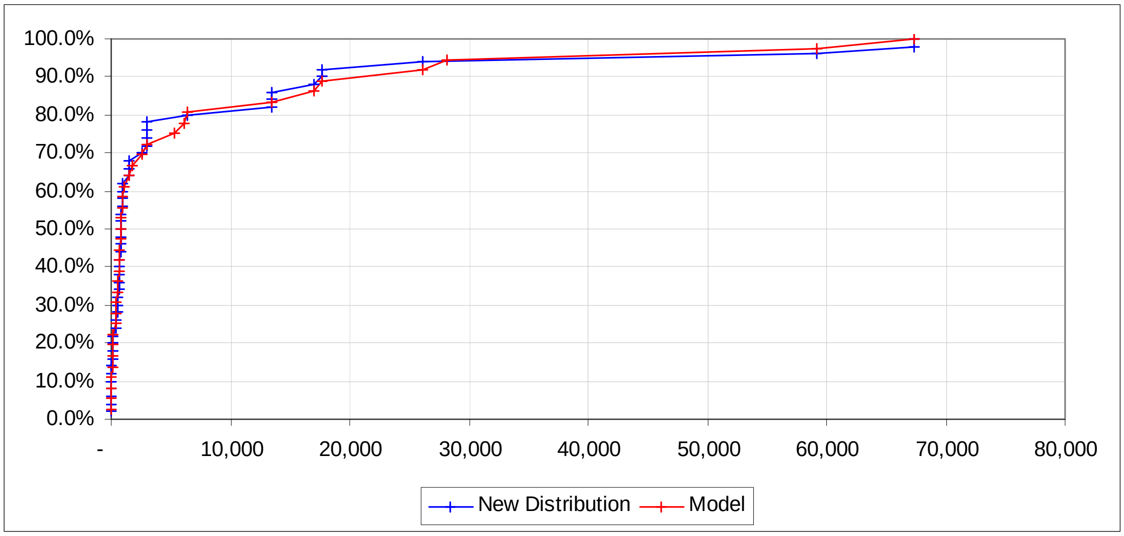


Figure 16 Cumulative and Annual Recharge for the Historical and Predictive Model — North Fork



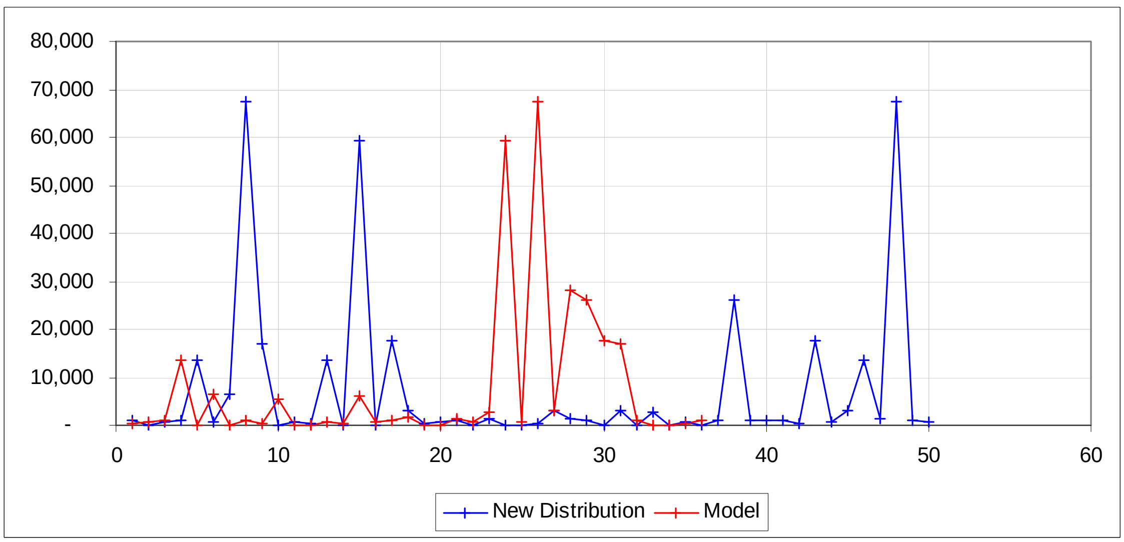
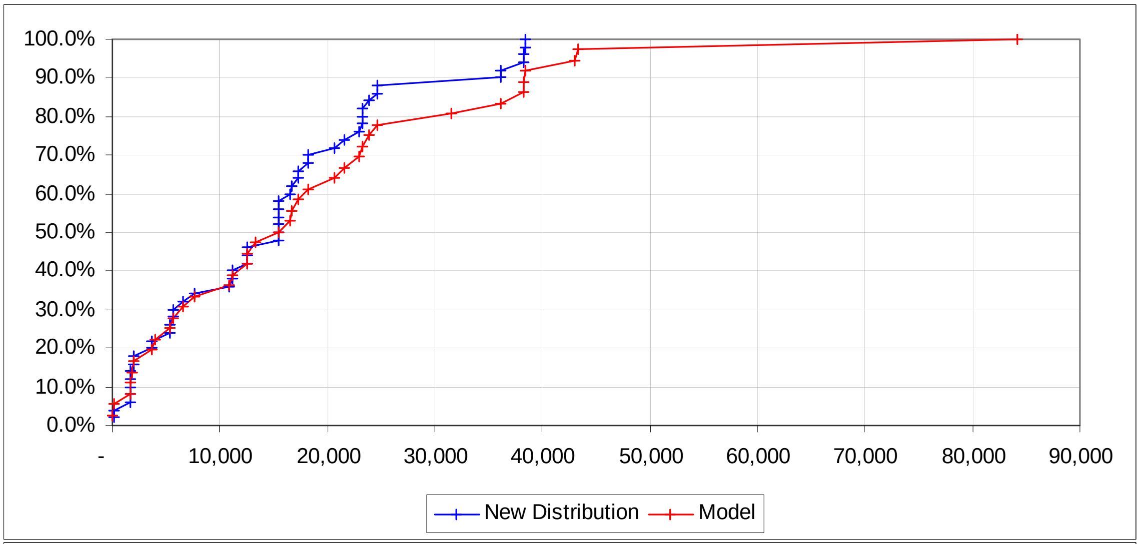


Figure 17 Cumulative and Annual Recharge for the Historical and Predictive Model — South Fork



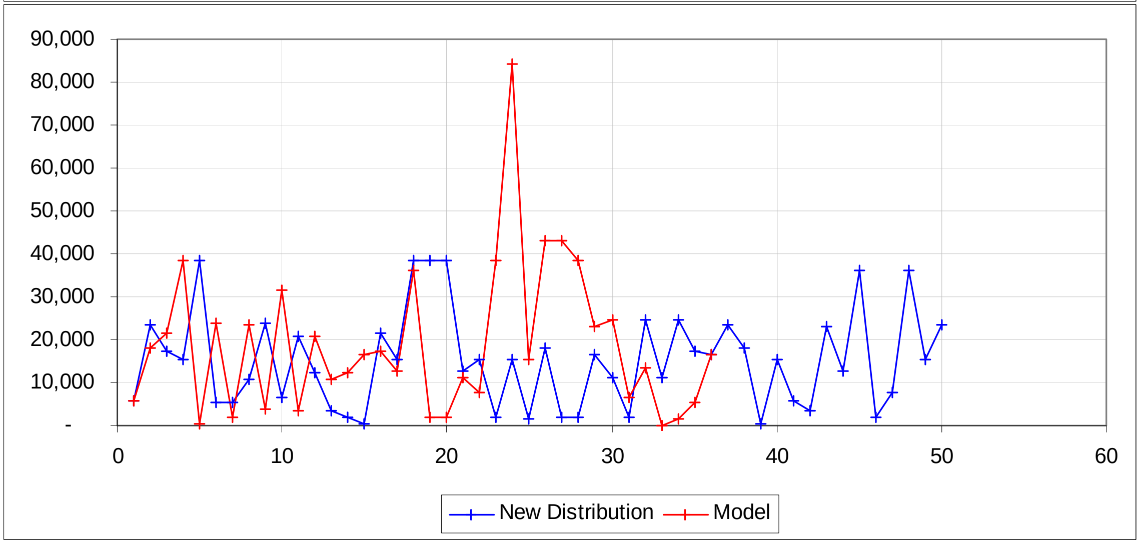


Figure 18 **Cumulative and Annual Recharge for the Historical and Predictive Model excluding Anomalously High Precipitation Years— North Fork**

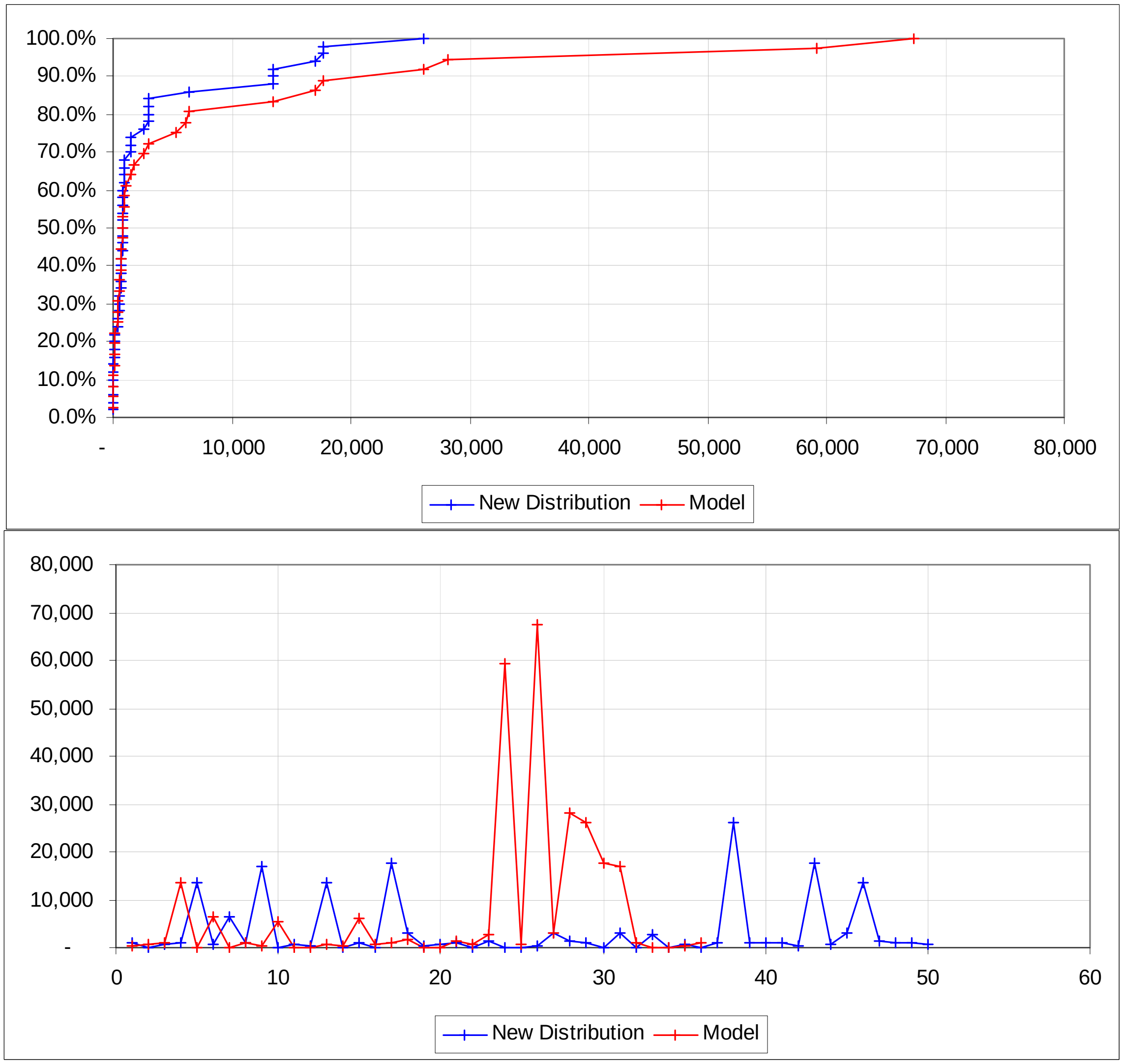


Figure 19 Cumulative and Annual Recharge for the Historical and Predictive Model excluding Anomalously High Precipitation Years— South Fork

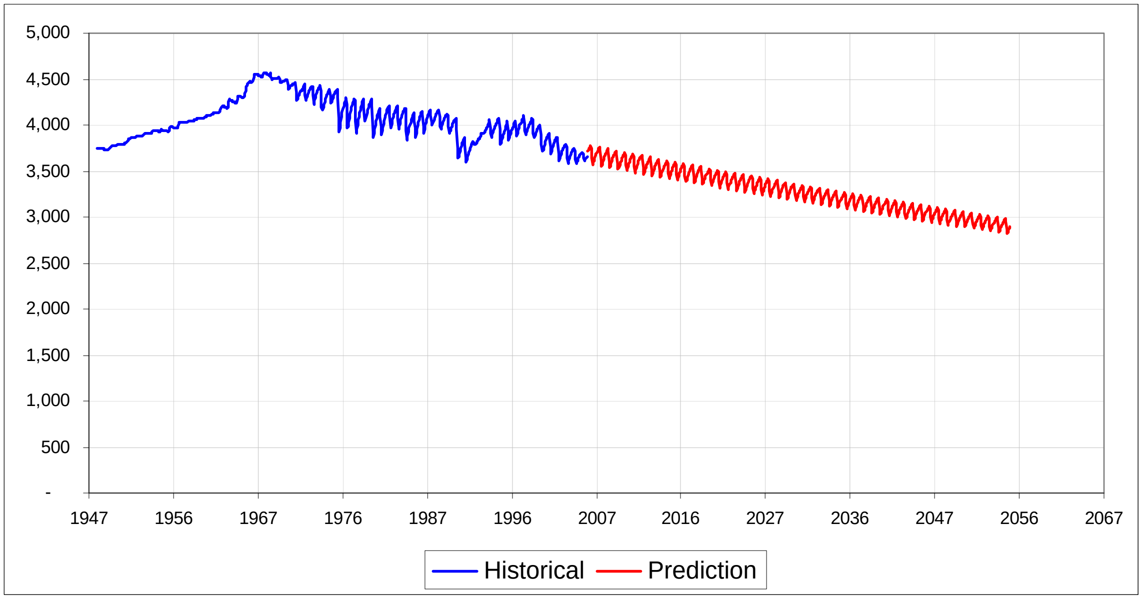


Figure 20 Boundary Flows for the Historical and Predictive Model — North Fork

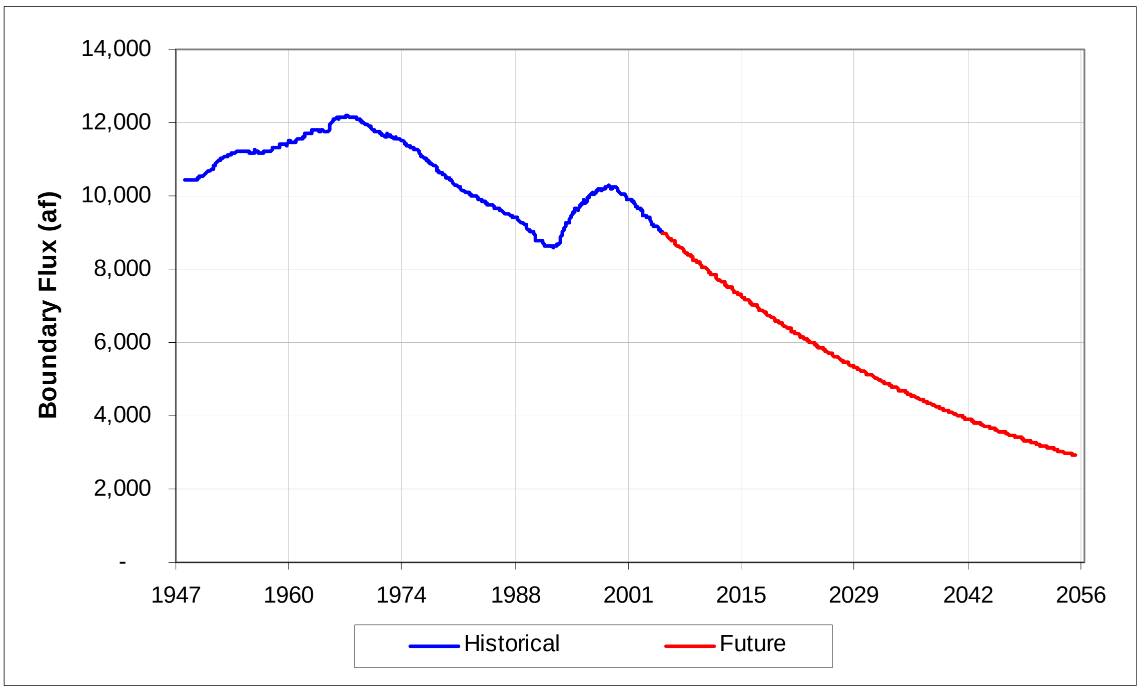


Figure 21 Boundary Flows for the Historical and Predictive Model — South Fork

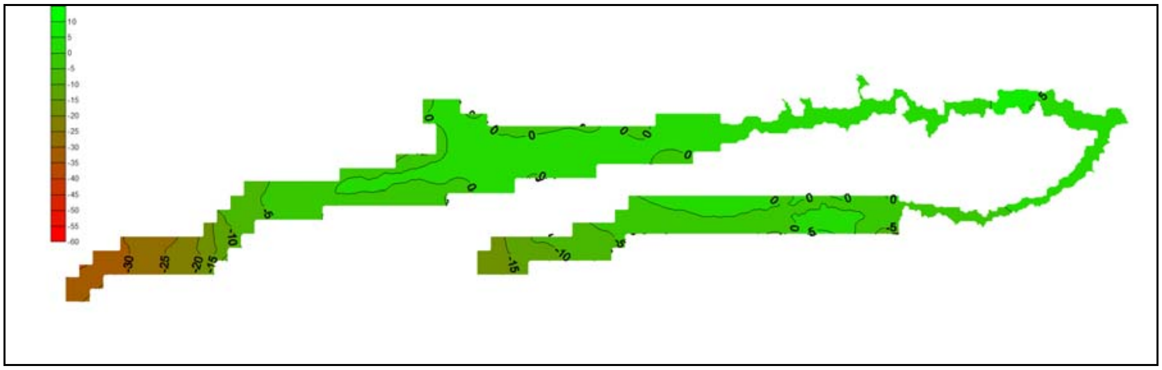


Figure 22 Future Dradown — Only Alluvium Pumping, North Fork

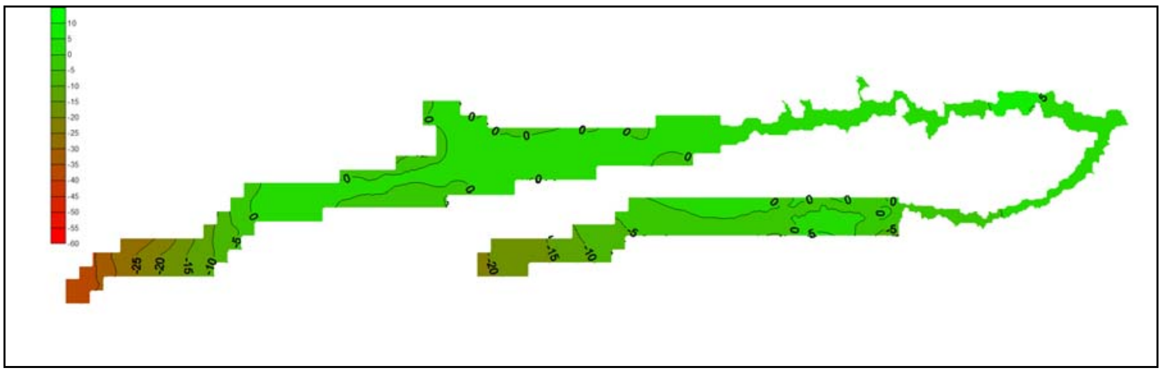


Figure 23 Future Drawdown — Only Ogallala Pumping, North Fork

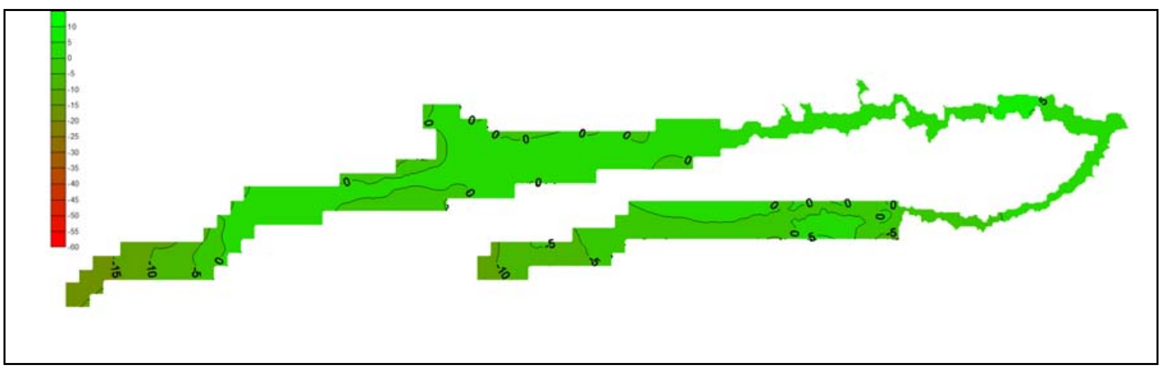


Figure 24 Future Drawdown — No Pumping, North Fork

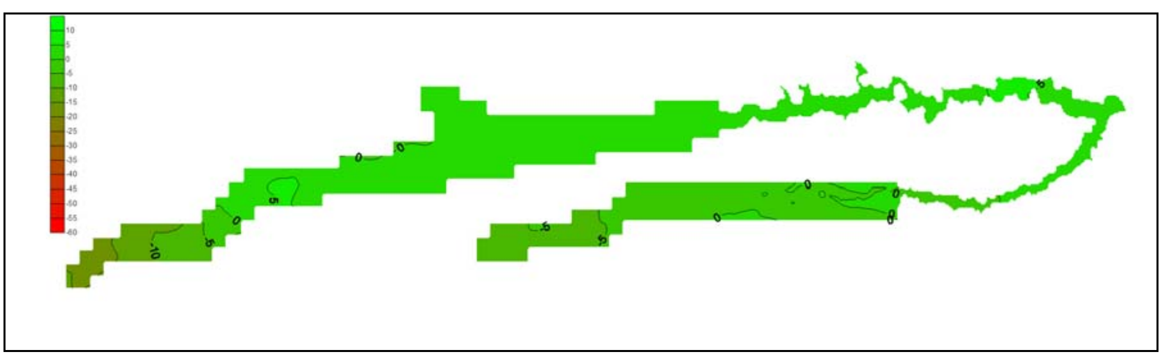


Figure 25 Future Drawdown — No Pumping and No Trend in Boundary Flows, North Fork

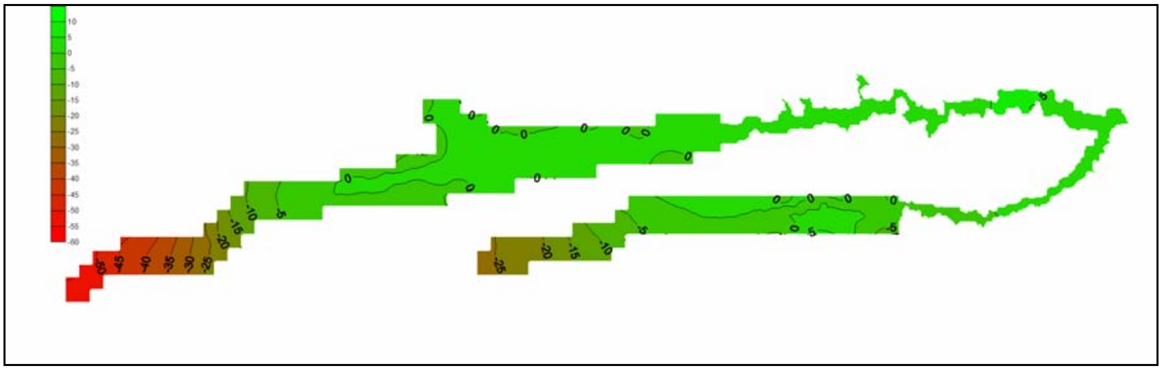


Figure 26 Future Drawdown — Lower ET, North Fork

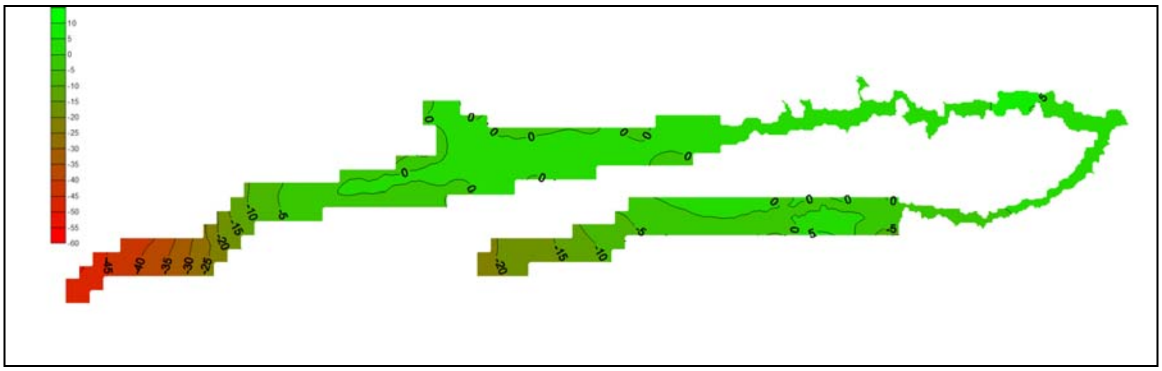


Figure 27 Future Drawdown — No Pumping from Marginal Soils, North Fork

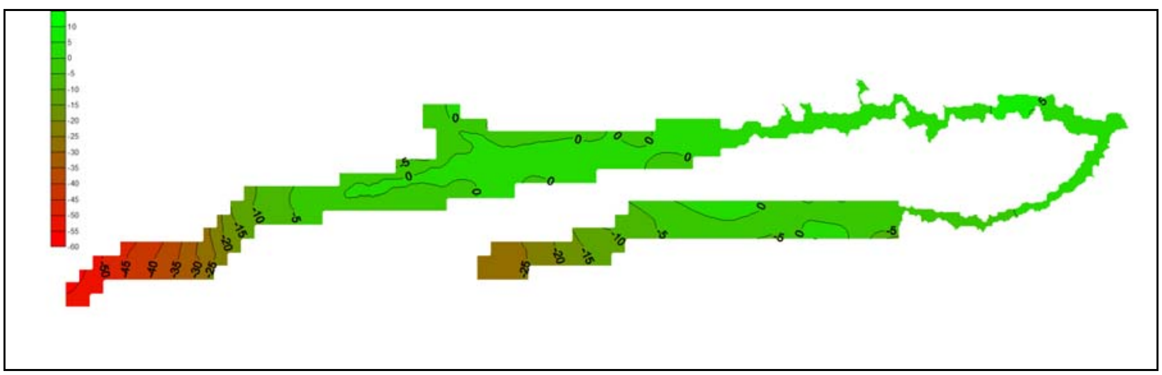


Figure 28 Future Drawdown — No Anomalously High Precipitation, North Fork

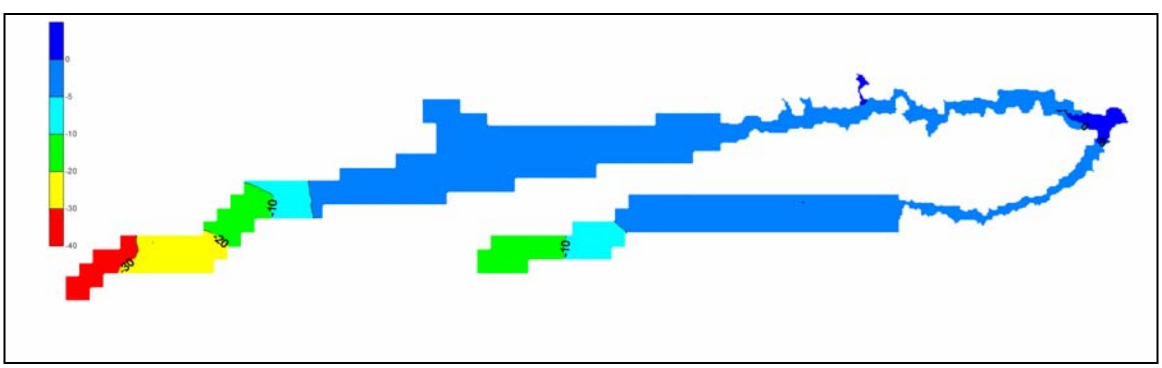


Figure 29 Future Drawdown Status Quo versus No Pumping, North Fork

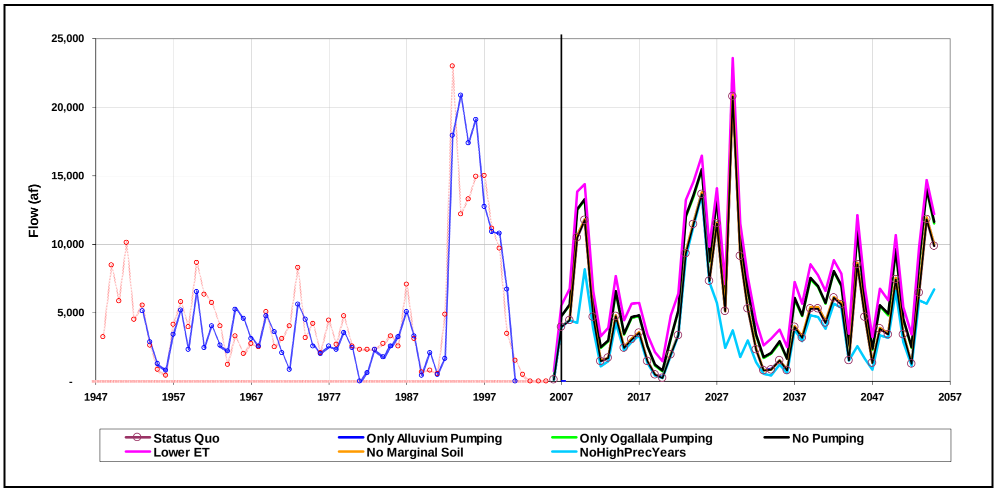


Figure 30 Historical and Future Baseflow — North Fork

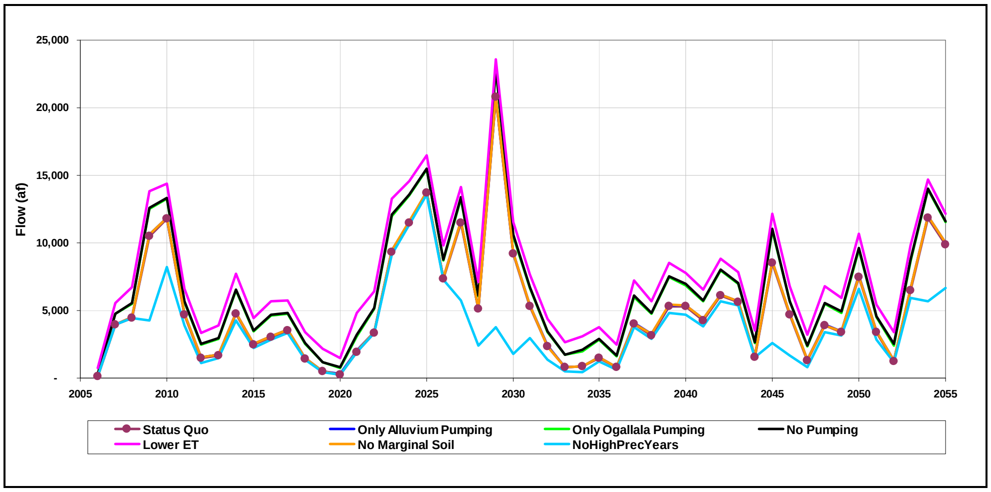


Figure 31 Future Baseflow — North Fork

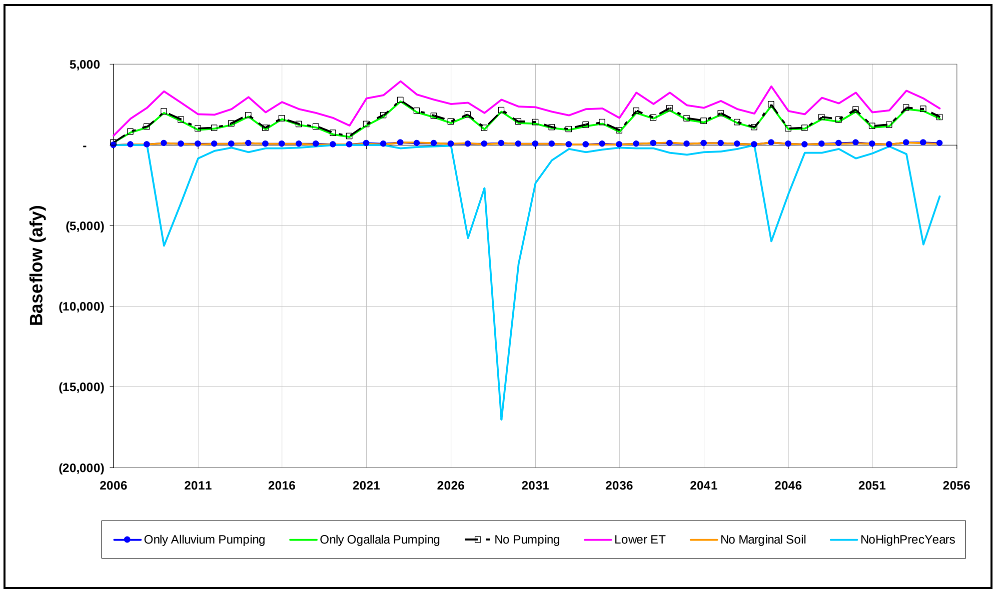


Figure 32 Difference in Baseflow for Alternative Scenarios from the Status Quo Scenario — North Fork

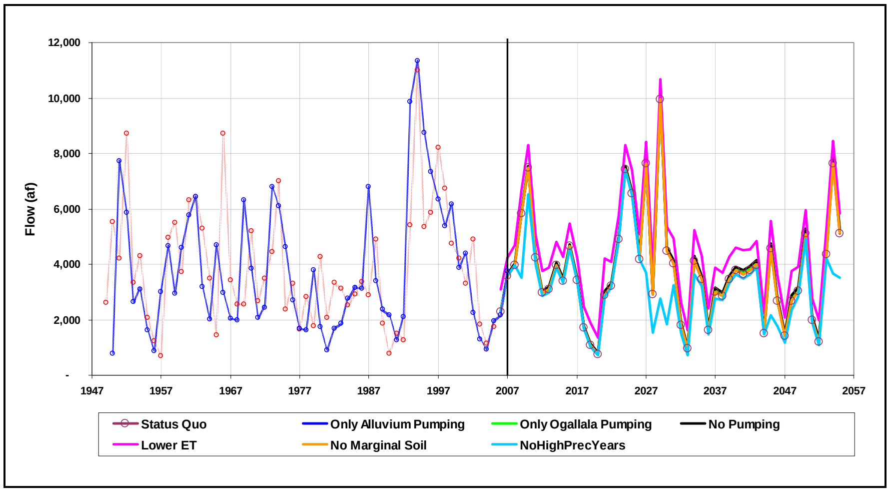


Figure 33 Historical and Future Baseflow — Bow Creek

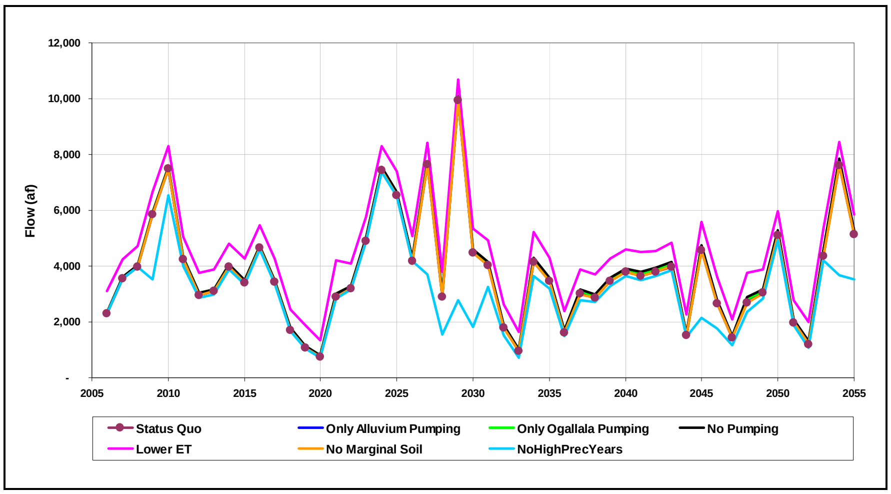


Figure 34 Future Baseflow —Bow Creek

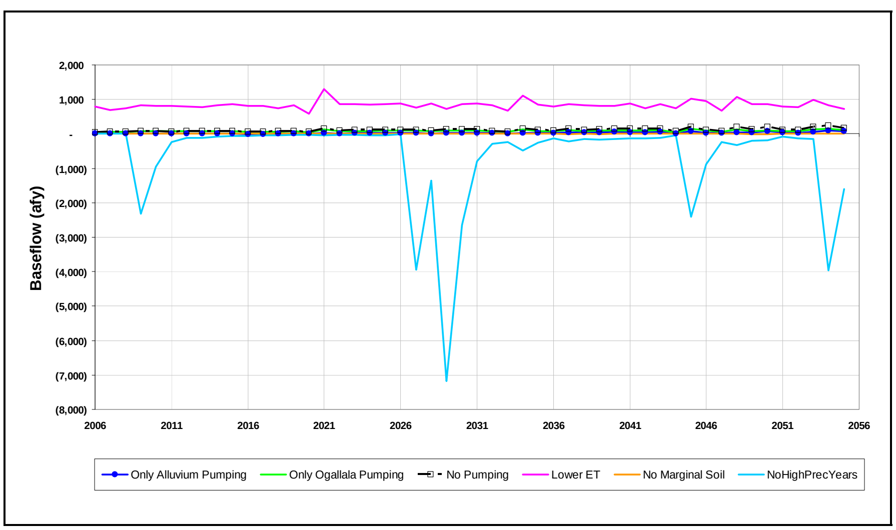


Figure 35 Difference in Baseflow between Alternative Scenarios and Status Quo – Bow Creek

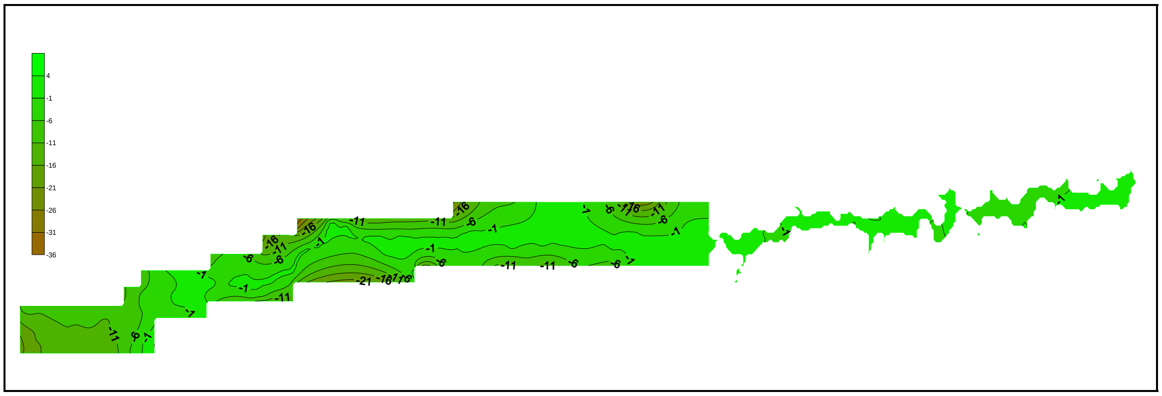


Figure 36 Future Drawdown — Only Alluvium Pumping, South Fork

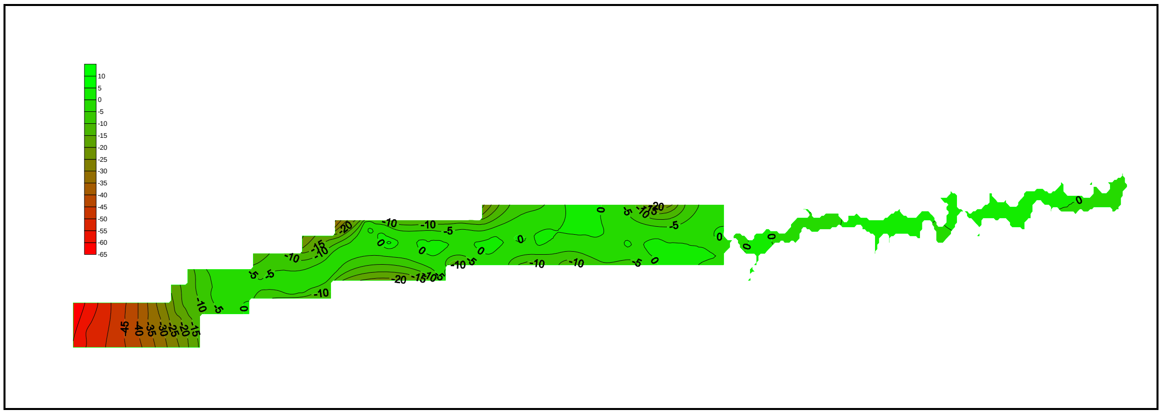


Figure 37 Future Drawdown — Only Ogallala Pumping, South Fork

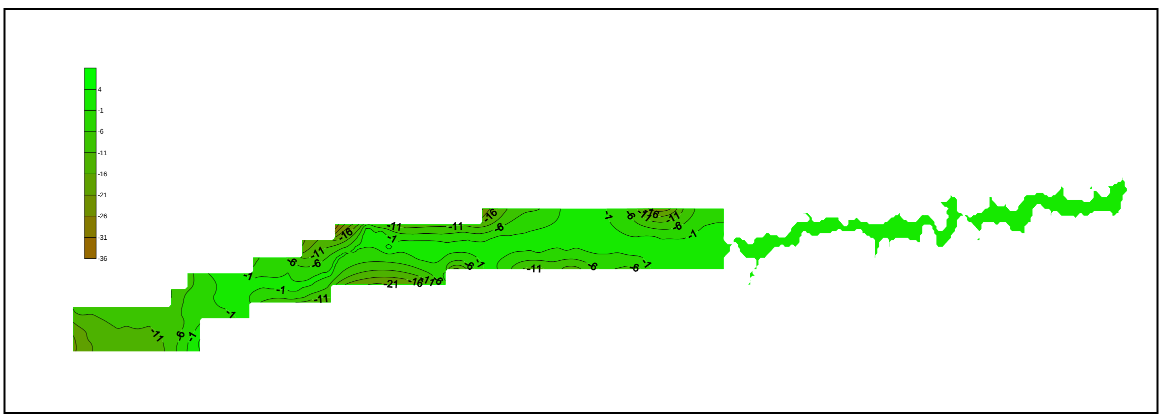


Figure 38 Future Drawdown — No Pumping, South Fork

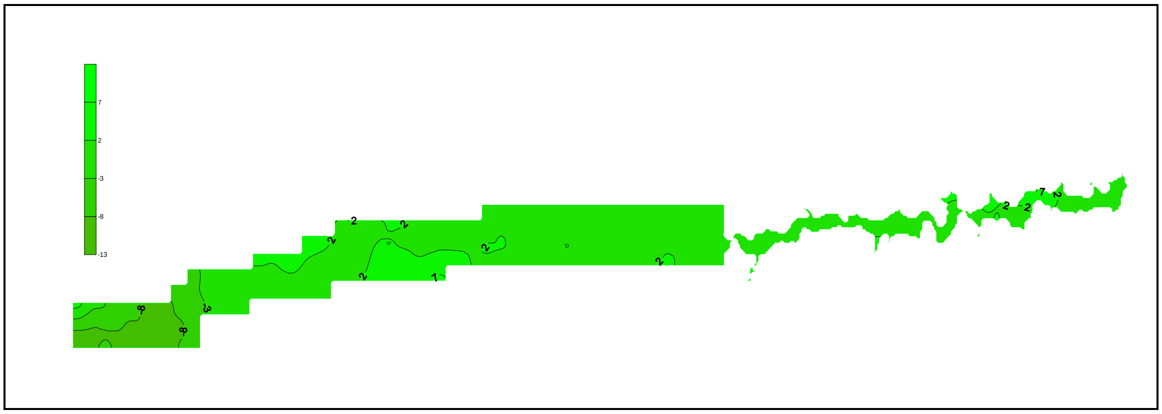


Figure 39 Future Drawdown — No Pumping and No Trend in Boundary Flows, South Fork

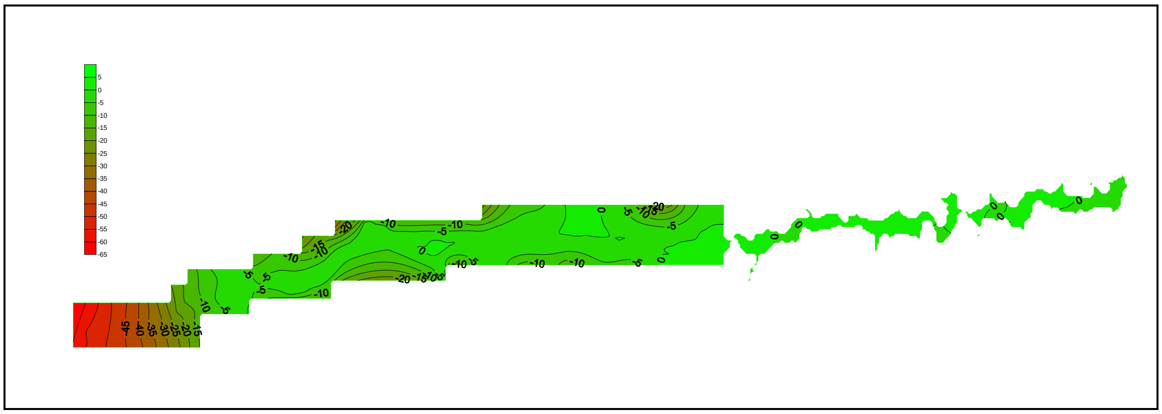


Figure 40 Future Drawdown — Lower ET, South Fork

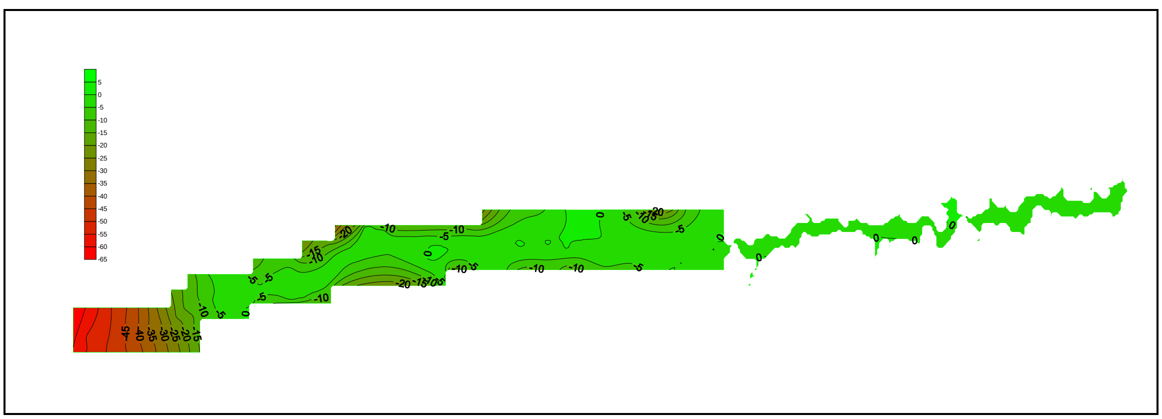


Figure 41 Future Drawdown — No Pumping from Marginal Soils, South Fork

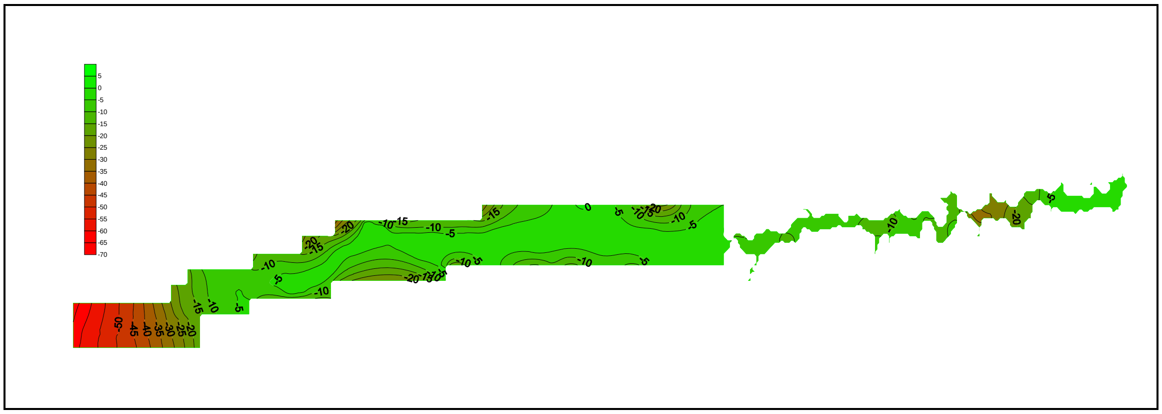


Figure 42 Future Drawdown — No Anomalously High Precipitation, South Fork

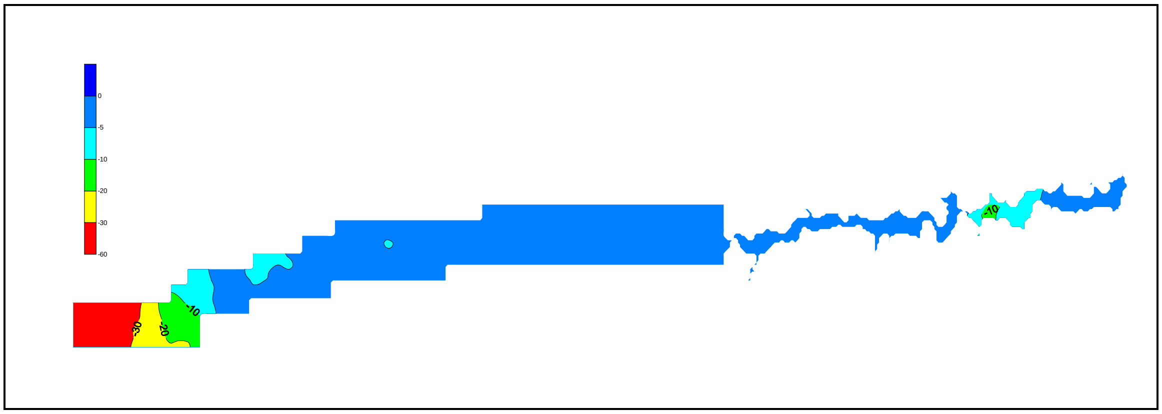


Figure 43 Future Drawdown Status Quo versus No Pumping, South Fork

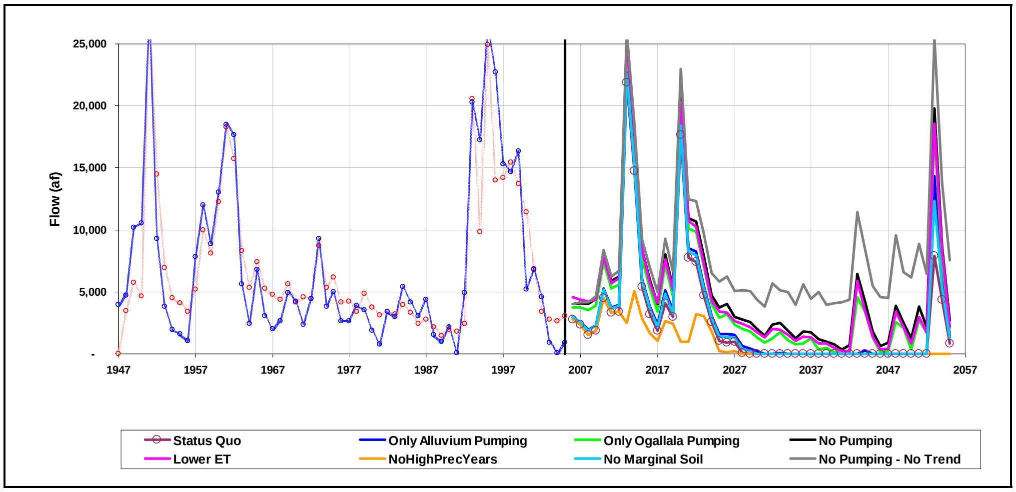


Figure 44 Historical and Future Baseflow — South Fork

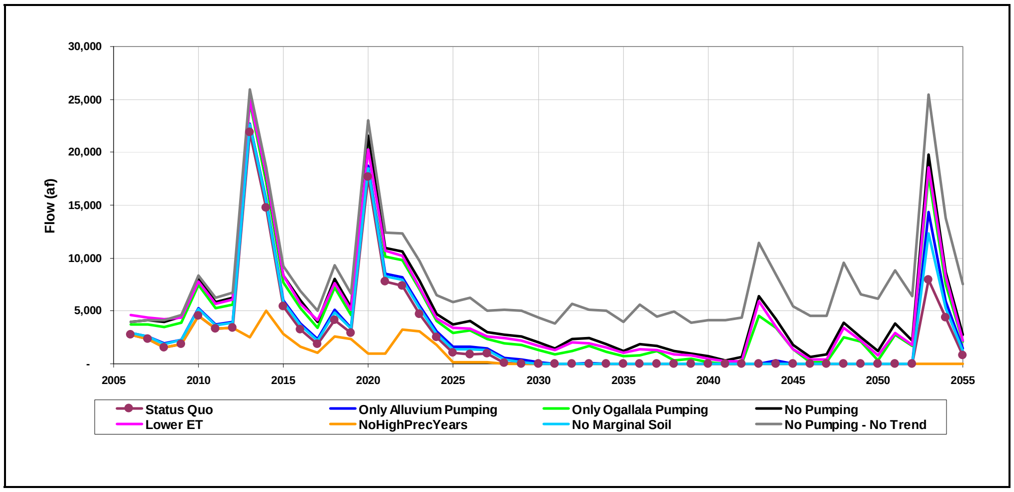


Figure 45 Future Baseflow — South Fork

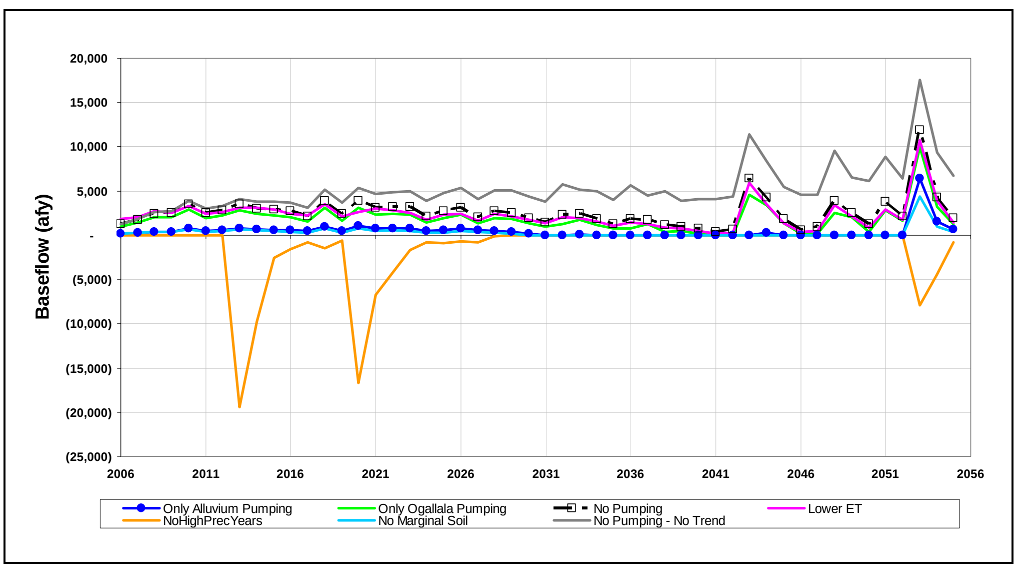


Figure 46 Difference in Baseflow between Alternative Scenarios and Status Quo — South Fork

TABLES

Table 1

Power Function Curve Parameters

Soil Type	Land Use	Power, n	Threshold, P_0	Coefficient, A
Coarse	Non-Irrigated	1.35	9	0.120
	Irrigated	1.50	4	0.060
Medium	Non-Irrigated	1.20	15	0.175
	Irrigated	1.70	6	0.025
Fine	Non-Irrigated	1.20	16	0.055
	Irrigated	1.45	2	0.020
AlluvX	Non-Irrigated	1.60	15	0.090
	Irrigated	1.60	15	0.097
AlluvY	Non-Irrigated	1.65	9	0.024
	Irrigated	1.55	11	0.045

Table 2

Groundwater Budget Summary — North Fork

	Storage	CHD	Wells	River	ET	Recharge	Stream
HISTORICAL	**3,533**	**-**	**(3,210)**	**(2,597)**	**(11,247)**	**22,403**	**(8,889)**
Status Quo	**4,501**	**-**	**(5,748)**	**(8,043)**	**(7,192)**	**22,040**	**(5,563)**
Only Alluvial Pumping	**2,803**	**-**	**(3,940)**	**(8,055)**	**(7,209)**	**22,040**	**(5,645)**
Diff from Status Quo	*1,698*	*-*	*(1,808)*	*12*	*18*	*-*	*82*
Only Ogallala Pumping	**2,474**	**-**	**(1,808)**	**(8,238)**	**(7,352)**	**22,040**	**(7,123)**
Diff from Status Quo	*2,027*	*-*	*(3,940)*	*195*	*161*	*-*	*1,560*
No Pumping	**802**	**-**	**-**	**(8,247)**	**(7,390)**	**22,040**	**(7,211)**
Diff from Status Quo	*3,699*	*-*	*(5,748)*	*205*	*198*	*-*	*1,648*
Lower ET	**4,425**	**-**	**(5,748)**	**(8,538)**	**(3,664)**	**22,040**	**(8,519)**
Diff from Status Quo	*76*	*-*	*-*	*495*	*(3,528)*	*-*	*2,956*
No Marginal Soil Pumping	**4,165**	**-**	**(5,326)**	**(8,054)**	**(7,195)**	**22,040**	**(5,635)**
Diff from Status Quo	*336*	*-*	*(422)*	*11*	*4*	*-*	*72*
No Anomalously High Precip	**5,083**	**-**	**(5,748)**	**(7,410)**	**(7,120)**	**18,454**	**(3,263)**
Diff from Status Quo	*(582)*	*-*	*-*	*(633)*	*(72)*	*3,586*	*(2,300)*

Table 3

Baseflow Summary — North Fork

	North Fork	Bow Creek	Total
HISTORICAL	4,776	3,897	8,672
	4,770	*3,810*	*8,580*
Status Quo	4,445	3,259	7,704
Only Alluvial Pumping	4,504	3,281	7,785
Diff from Status Quo	*59*	*22*	*81*
Only Ogallala Pumping	5,667	3,333	8,999
Diff from Status Quo	*1,222*	*74*	*1,296*
No Pumping	5,729	3,356	9,084
Diff from Status Quo	*1,284*	*97*	*1,381*
Lower ET	6,547	3,986	10,533
Diff from Status Quo	*2,102*	*727*	*2,829*
No Marginal Soil Pumping	4,502	3,260	7,762
Diff from Status Quo	*57*	*2*	*59*
No Anomalously High Precip	3,157	2,687	5,844
Diff from Status Quo	*(1,288)*	*(571)*	*(1,860)*

Table 4

Groundwater Budget Summary — South Fork

	Storage	Wells	River	ET	Recharge	Stream
HISTORICAL	**995**	**(2,869)**	**(1,387)**	**(9,325)**	**18,860**	**(6,274)**
Status Quo	**3,949**	**(5,946)**	**(2,428)**	**(6,437)**	**12,465**	**(1,606)**
Only Alluvial Pumping	**2,001**	**(3,364)**	**(2,493)**	**(6,742)**	**12,465**	**(1,871)**
Diff from Status Quo	*1,948*	*(2,582)*	*65*	*305*	*-*	*265*
Only Ogallala Pumping	**3,560**	**(2,582)**	**(2,915)**	**(7,510)**	**12,465**	**(3,022)**
Diff from Status Quo	*389*	*(3,364)*	*487*	*1,073*	*-*	*1,416*
No Pumping	**1,754**	**-**	**(3,069)**	**(7,692)**	**12,465**	**(3,463)**
Diff from Status Quo	*2,195*	*(5,946)*	*641*	*1,255*	*-*	*1,857*
No Pumping - No Trend	**115**	**-**	**(3,534)**	**(7,977)**	**16,725**	**(5,333)**
Diff from Status Quo	*3,834*	*(5,946)*	*1,106*	*1,540*	*(4,260)*	*3,727*
Lower ET	**3,679**	**(5,946)**	**(3,083)**	**(3,871)**	**12,465**	**(3,245)**
Diff from Status Quo	*270*	*-*	*655*	*(2,566)*	*-*	*1,639*
No Marginal Soil Pumping	**3,746**	**(5,097)**	**(2,519)**	**(6,719)**	**12,465**	**(1,880)**
Diff from Status Quo	*203*	*(849)*	*91*	*282*	*-*	*274*
No Anomalously High Precip	**5,189**	**(5,946)**	**(1,793)**	**(5,999)**	**8,635**	**(91)**
Diff from Status Quo	*(1,241)*	*-*	*(635)*	*(438)*	*3,829*	*(1,515)*

Table 5

Baseflow Summary — South Fork

	SouthFork
HISTORICAL (computed)	7,161
HISTORICAL (measured)	*6,981*
Status Quo	2,601
Only Alluvial Pumping	3,070
Diff from Status Quo	*469*
Only Ogallala Pumping	4,487
Diff from Status Quo	*1,885*
No Pumping	5,223
Diff from Status Quo	*2,621*
No Pumping - No Trend	7,787
Diff from Status Quo	*5,186*
Lower ET	4,886
Diff from Status Quo	*2,285*
No Marginal Soil Pumping	2,928
Diff from Status Quo	*327*
No Anomalously High Precip	967
Diff from Status Quo	*(1,634)*