Appendix C – Development of 2070 Unimpaired Hydrology

Introduction

Hydrologic projections for 2070 unimpaired flows were derived using simulated historical and projected 2070 surface runoff and baseflow from the Variable Infiltration Capacity (VIC) model (Liang et al. 1994). The VIC model is a gridded hydrologic model that simulates land-surface-atmosphere exchanges of moisture and energy at each model grid cell. The California Water Commission (CWC) provided VIC model data for the state of California on a grid spatial resolution of approximately 14 square miles for the period January 1915 through December 2011 for near future (2030) and late future (2070) climate periods (CWC 2016) . This analysis uses the 2070 predictions for the three scenarios provided by the CWC:

- Median climate change conditions, based on 20 global climate models (GCMs) and representative concentration pathway (RCP) combinations. The 20 climate model and RCP combinations are composed of 10 general circulation models, each run with two RCPs: one optimistic (RCP 4.5) and one pessimistic (RCP 8.5). This scenario represents the central tendency of the ensemble of general circulation models (GCMs);
- Drier/extreme-warming (DEW) conditions based on GCM HadGEM2-ES and emission scenario RCP 8.5, representing a pessimistic trajectory of greenhouse gas emissions throughout this century; and
- Wetter/moderate-warming (WMW) conditions based on GCM CNRM-CM5 and emission scenario RCP 4.5, representing an optimistic trajectory of greenhouse gas emissions throughout this century.

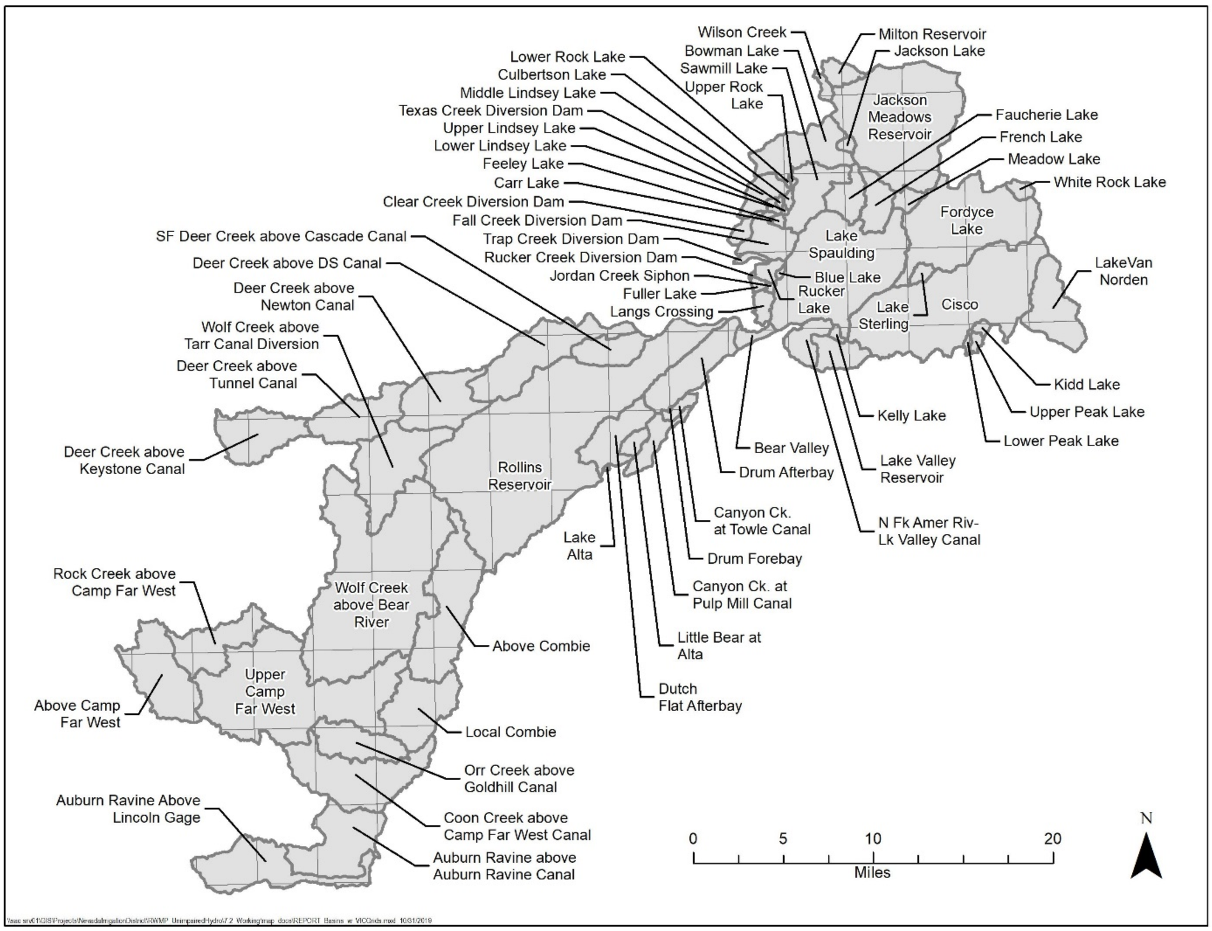
The CWC developed meteorology for the three 2070 climate projections by applying perturbations to the historical precipitation and temperature time series, a method known as “climate period analysis” (CWC 2016, DWR 2018). A benefit of this approach is that modeled future inter-annual variability is based on the reference period from which change is being measured, so all differences between the future and historical simulations are a result of the climate change signal alone (DWR 2018). As a result, each future scenario exhibits a similar temporal pattern and relative distribution of water year types as the historical record. A disadvantage of this approach is that predicted changes in inter-annual variability, such as the potential for extended droughts, is not represented in the data.

The VIC model data were used to translate gage-proration historical unimpaired hydrology into projected unimpaired hydrology for Water Years 1976 to 2011. The lower bound of 1976 was chosen based on availability of stream gage data used for development of the gage-proration unimpaired hydrology data set. The upper bound of 2011 is based on the available period of record of projected hydrologic data provided by the CWC. Development of gage-proration unimpaired hydrology is documented in Appendix B of the Hydrologic Analysis Technical Memorandum.

Methods

A geographic information system (GIS) was used to overlay the unimpaired hydrology sub-basin boundaries on the VIC model grid (Figure C-1). Total VIC Model daily runoff depth (in millimeters) was calculated for each sub-basin as the area-weighted average of the sum of surface runoff and baseflow from VIC grid cells completely contained within the sub-basin boundary and from partial grid cells intersected by the basin boundary. Daily sub-basin-averaged VIC runoff depths were generated for each unimpaired hydrology sub-basin for all three 2070 climate projection scenarios and the historical scenario provided by the CWC.

Figure C-1. Unimpaired hydrology sub-basins divided by VIC grid cells.



VIC model daily runoff depths were converted to mean-daily flows in cubic feet per second (cfs) by multiplying by the sub-basin areas and applicable conversion factors. A comparison of historical VIC model flows to gage-proration flows indicates significant differences in timing and volume of flows. Figure C-2 illustrates the correlation coefficient of 0.74 for daily runoff in the 41.3 square mile Cisco Sub-basin, used as an example. There is a tighter correlation on an annual time scale (Figure C-3), although VIC model flows are approximately 28 percent greater than gage-proration flows. The exceedance diagram in Figure C-4 further illustrates the significant differences in annual volumes. The monthly temporal distribution of flows exhibits a similar pattern, as shown in Figure C-5. Both gage-proration flows and VIC model flows peak in May as a result of snowmelt in the higher elevation basin, although VIC model flows are slightly higher from January through March and slightly lower from April through December.

Figure C-2. Comparison of gage-proration and VIC model historical mean-daily runoff at Cisco Sub-Basin.

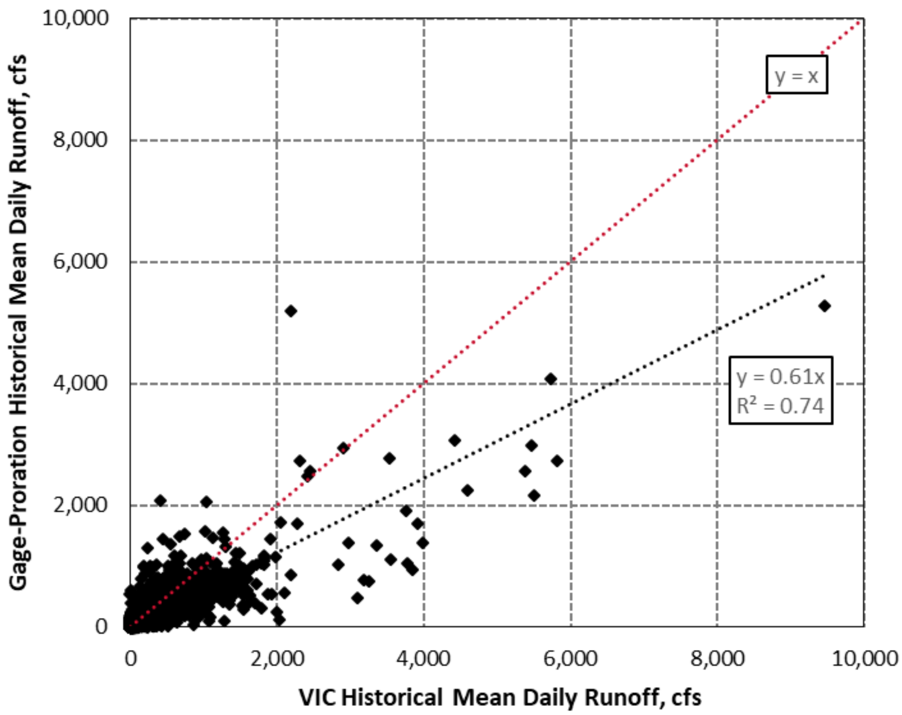


Figure C-3. Comparison of gage-proration and VIC model historical mean-annual runoff at Cisco Sub-Basin.

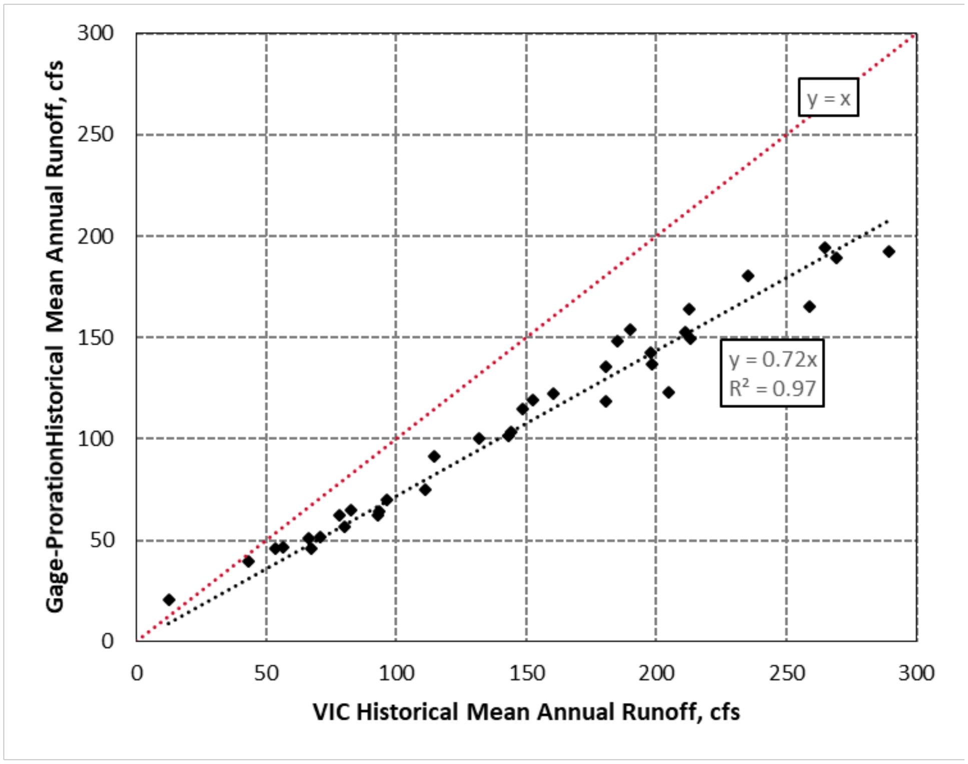


Figure C-4. Comparison of gage-proration and VIC model historical mean-annual runoff probability of exceedance at Cisco Sub-Basin.

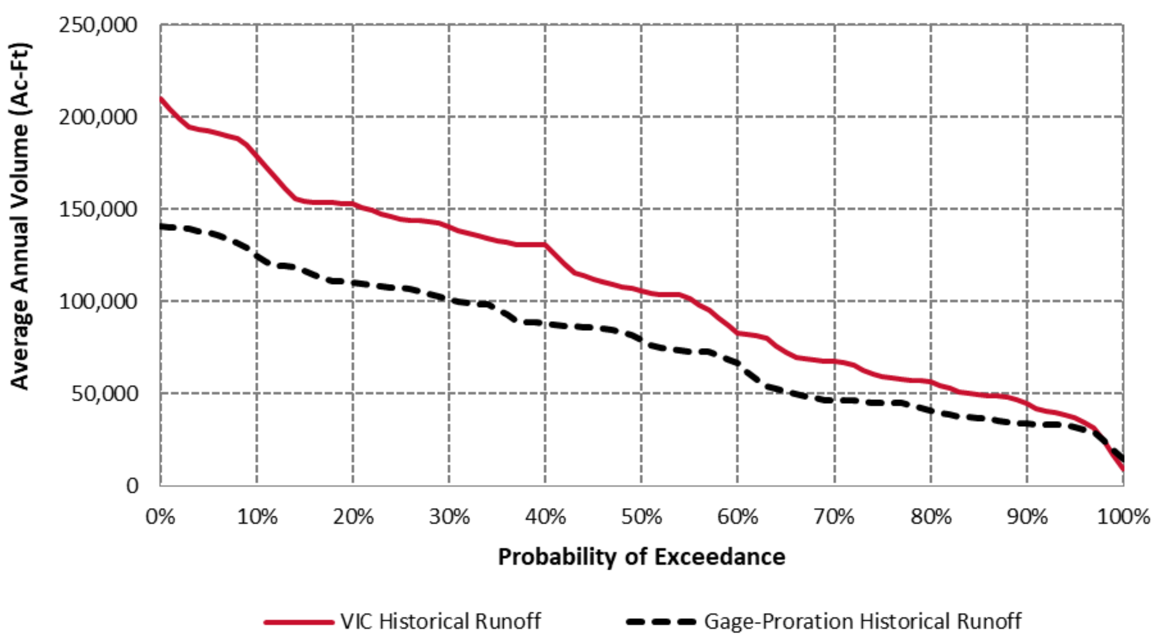
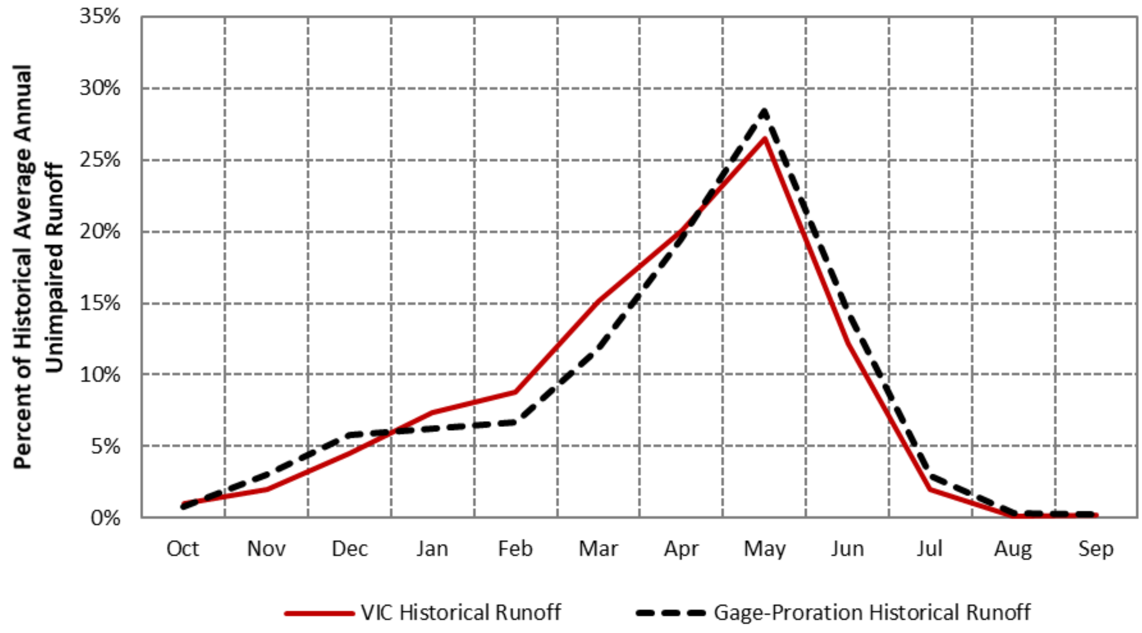


Figure C-5. Comparison of gage-proration and VIC model historical monthly runoff at Cisco Sub-Basin.



The differences between VIC model flows and gage-proration flows arise from a number of contributing factors including, but not limited to:

- The VIC model was calibrated for 12 large upper watersheds in the Sacramento and San Joaquin River basins for water years 1970 through 2003 (CWC 2016). However, the sub-basins in this study are much smaller than the VIC model calibration basins and do not have unimpaired stream gage data to allow calibration;
- A small number of VIC model grid cells are intersected by each sub-basin, a potential significant source of error. The VIC model is more accurate at a watershed scale where a large number of grid cells are intersected and routing is added to the simulation (CWC 2016);
- Prorating grid cell runoff by the ratio of intersected area assumes a uniform spatial distribution of flow at the scale of the VIC model grid cell and ignores the impact of local watershed boundaries and routing;
- There are potential spatial and temporal errors in down-scaled gridded climate data used as driving input to the VIC model (CWC 2016);
- VIC model uncertainty, including complexities of snowmelt simulation, base flow and groundwater interactions, and simulated losses;
- Gage-proration unimpaired flows were derived using hydrographs from a small number of reference basins, as described in Appendix B of the Hydrologic Analysis Technical Memorandum. This method assumes similar hydrologic behavior between reference and target basins.

The gage-proration historical hydrology is used as the baseline data set for this study. This choice is based on the successful verification using the FERC relicensing operations model (Devine Tarbell & Associates 2008) and alignment with monthly gage–summation flow volumes as described in Appendix B.

A bias correction approach is needed to address the modeled differences in volume and timing of historical unimpaired flows to effectively use the VIC Model results for prediction of future hydrology. There is no standardized method for bias correction and different approaches can yield significantly different results (Pierce et al. 2015). We chose an approach based on the variable perturbation method used in California's fourth climate change assessment to estimate impacts on the State Water Project (Wang et al. 2018). This method is similar to the cumulative distribution function transform (CDF-t) bias correction described by Pierce (2015). The VIC Model projected sub-basin flows were bias-corrected using CDF-t applied first to daily flows using a month-long time window, and subsequently to annual flows. The CDF-t method assumes that the historical mapping between the model and observed cumulative distribution functions applies to the future period (Pierce et al. 2015). Each step is described in detail in the following sections and can be followed for the Cisco example sub-basin in the accompanying Appendix C spreadsheet.

Step 1. Sub-Basin Correlations for Historical Unimpaired Hydrology

The correlations between historical VIC model runoff depths and gage-proration daily flows were calculated for all sub-basin pairs. The results indicate that, in general, the best correlation did not occur between the geographically paired basins as a result of the bias errors and differences in model types and assumptions bulleted in the previous section. The correlation coefficients are shown in worksheet "Step 1" of the Appendix C spreadsheet. The diagonal set of cells outlined in black indicates the correlations with geographically corresponding sub-basins. The cells highlighted in red indicate the best correlated sub-basins.

The gage-proration method used to develop the historical unimpaired hydrology results in some degree of self-similarity of constructed flows in different sub-basins based on the limited number of reference basins used; thus, it is not surprising that a small number of VIC model sub-basins correlate best to a number of different gage-proration sub-basins in the same region. In general, the VIC Model Combie basin flows were best correlated with the lower-elevation watersheds, Cisco (also used as a gage-proration reference basin for upper-elevation watersheds in the FERC study) was best correlated with the upper-elevation watersheds, and Jackson Lake was best correlated with the highest watersheds. There were a few exceptions as noted in Table C-1.

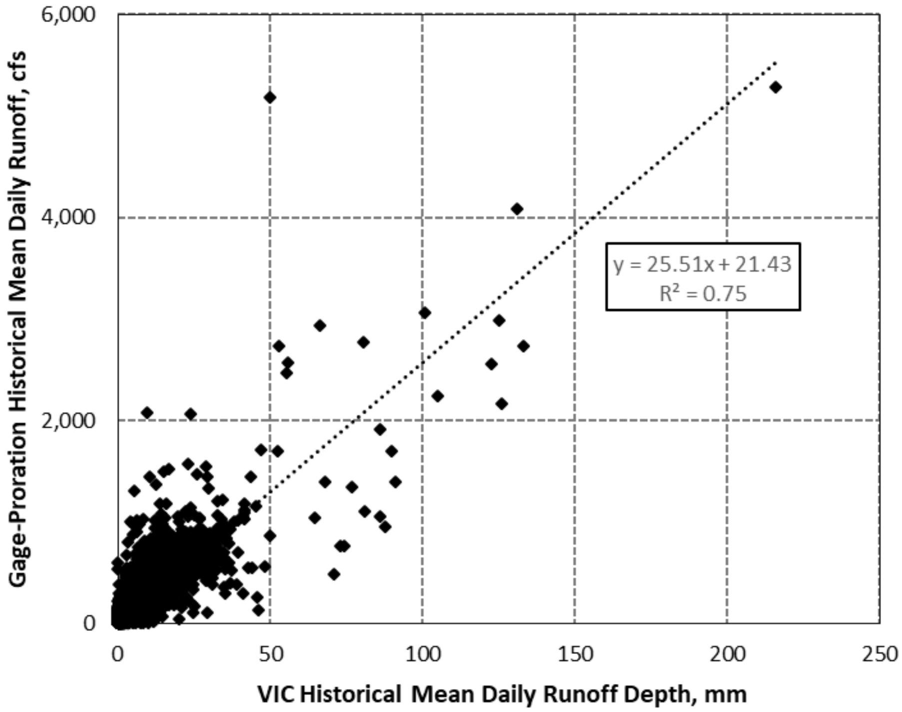
Table C-1. VIC Model Reference Basins used for Hydrology Analysis

Gage-Proration Hydrology Basin	VIC Model Reference Basin	Average Correlation Coefficient
Most Lower-Basin Watersheds	Lake Combie	0.84
Most Upper-Basin Watersheds	Cisco	0.86
SYR above Kidd Lake	Jackson Lake	0.87
Lake Sterling	Jackson Lake	0.87
Fordyce Lake	Jackson Lake	0.87
French Lake	Jackson Lake	0.87
Faucherie Lake	Jackson Lake	0.86
Jackson Lake	Jackson Lake	0.86
Upper Lindsey Lake	Jackson Lake	0.86
White Rock Lake	Jackson Meadows Reservoir	0.87
Meadow Lake	Jackson Meadows Reservoir	0.87
Langs Crossing	Kidd Lake	0.85
Canyon Ck above Towle Canal Div Dam	Trap Creek Diversion Dam	0.76
Canyon Ck above Pulp Mill Impoundment	Trap Creek Diversion Dam	0.76
Canyon Ck Headwaters	Upper Peak Lake	0.81

Step 2. VIC Model Historical and Future Flows

Linear regression was used to convert the best-correlated VIC model sub-basins historical and projected 2070 runoff depths to flows in cubic feet per second for each sub-basin. This approach preserves the gage-proration mean flow, but may overestimate low flows in some sub-basins because of the addition of the regression intercept. The impact of errors associated with this approach are mitigated by the subsequent procedures used to generate perturbation ratios to transform historical gage-proration flows to future flows based on cumulative distribution functions (CDFs). The slope and intercept regression values for each sub-basin are shown in rows 5 and 6 of the correlation table in worksheet “Step 1”. The regression for the Cisco sub-basin is illustrated in Figure C-6. The linear transformations applied to the Cisco example sub-basin for the historical and Median climate change scenario runoff depths are shown in worksheet “Step 2”.

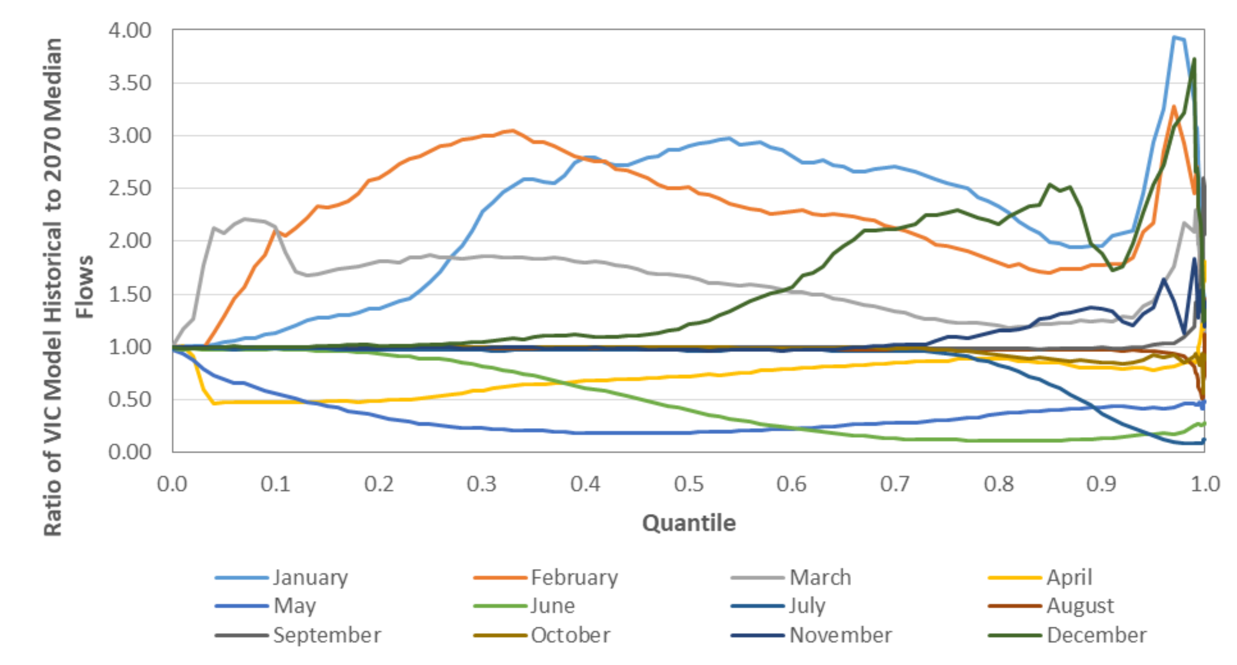
Figure C-6. Linear regression between Cisco sub-basin historical runoff depths and gage-proration historical flow.



Step 3. Monthly CDFs and Perturbation Ratios

Calculate CDFs of the VIC model historical and projected flows for each calendar month and determine the ratio of projected to historical flows at each quantile. The calculation is shown for the Median scenario for the Cisco example sub-basin in worksheet "Step 3" of the Appendix C spreadsheet. The ratios will be used as multiplicative factors to perturb the gage-proration historical flows, as described in Step 4. The method is based on the assumption that the mapping between the historical VIC model and gage-proration hydrology applies to the future hydrology. The distribution of ratios by quantile varies for each month, ranging from 0.08 to 3.93, as illustrated in Figure C-7. Ratios greater than one generally occur from December through March. Ratios less than one generally occur in April, May and June.

Figure C-7. Monthly perturbation ratios versus quantile for Cisco sub-basin.



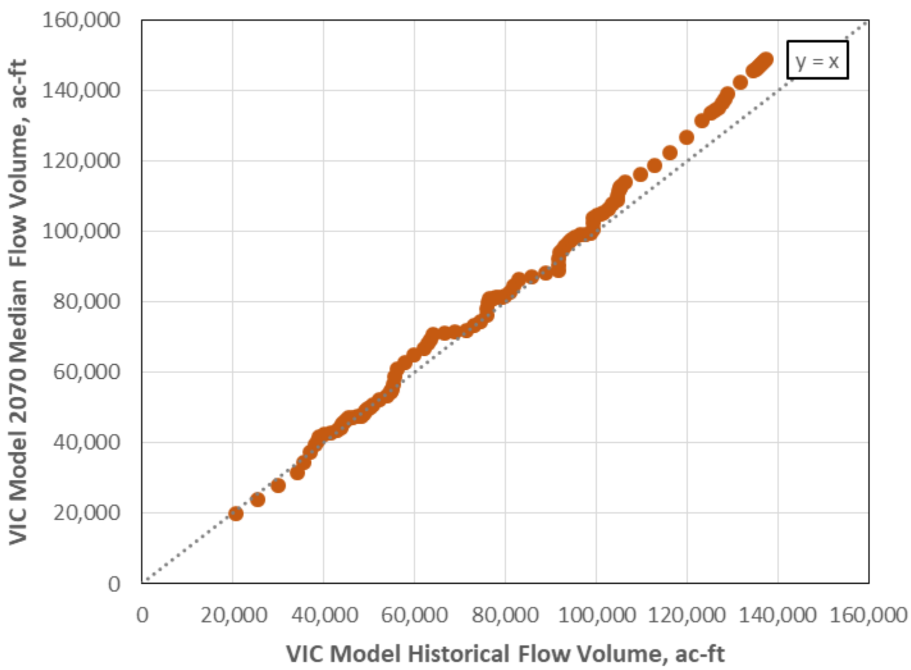
Step 4. Apply Monthly Perturbation Ratios to Gage-Proration Historical Flows

Map each gage-proration historical daily flow to the corresponding VIC Model historical quantile associated with that flow in the corresponding month. The interpolated ratio of VIC Model projected flow to VIC Model historical flow for that CDF quantile is used as the perturbation ratio for that daily historical flow. A perturbation ratio was determined for each day in the historical record. Historical daily flow may fall outside the bounds of the historical VIC Model flows in any given month because of model biases and methods used to convert runoff depths to flows. For these cases the values at the bounds of the CDFs were used to define the perturbation ratio which may introduce some error in the prediction of extreme flows. This occurred primarily for low flows, for which perturbation ratios were close to or equal to one in all months, so any impact is likely to be small. The high flow boundary was exceeded for less than 0.04 percent of daily values overall. The calculation is shown for the Cisco sub-basin in worksheet “Step 4”.

Step 5. Annual CDFs and Perturbation Ratios

Calculate total annual flow volume for the gage-proration historical flow, gage-proration historical flow perturbed by the monthly CDF ratios, VIC model historical and projected 2070 daily flow volumes, as shown in worksheet “Step 5a”. Calculate CDFs of VIC model historical and projected 2070 annual flows to determine perturbation ratios using the same method as used for monthly flows described in Step 3, demonstrated in worksheet “Step 5b”. The comparison of VIC model historical to VIC model 2070 Median annual flow volumes at each quantile is shown in Figure C-8. The figure indicates that the driest years are predicted to be slightly drier in the 2070 Median scenario, and wet years are predicted to be wetter.

Figure C-8. Comparison of VIC model 2070 Median to historical flow volumes at each quantile for Cisco sub-basin.



Step 6. Apply Annual Perturbation Ratios to Perturbed Gage-Proration Historical Flows

Map each gage-proration historical annual total flow to the corresponding VIC model historical quantile associated with that flow. The interpolated ratio of VIC model projected flow to VIC model historical flow for that CDF quantile is used as the perturbation ratio for the gage-proration historical flows perturbed by the monthly ratios from Step 4. Interpolated annual quantile perturbation ratios for each year are calculated in worksheet “Step 5a” and applied in worksheet “Steps 6 through 8”.

Step 7. Adjust Perturbed Flows to Match Annual Quantile Volume Ratios

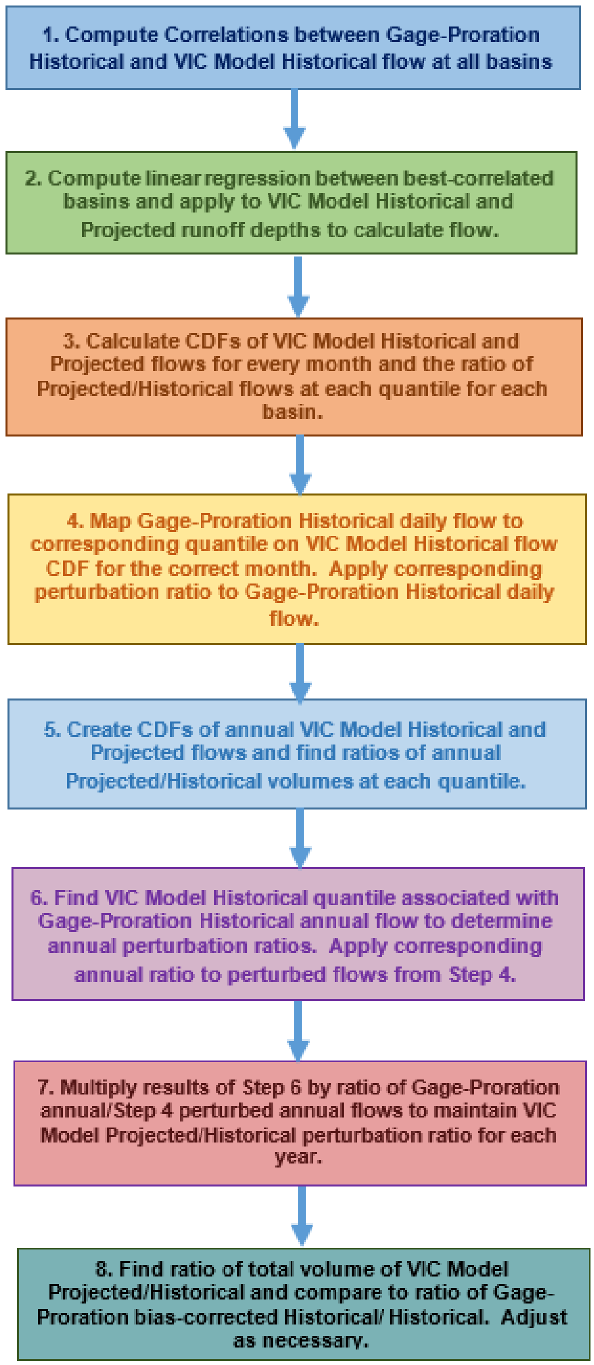
Multiply the results of Step 6 by the ratio of the annual volume of gage-proration historical flows to the annual volume of monthly quantile perturbed flows from Step 4 so that the final volume ratio of projected to historical annual flows is equivalent to the VIC model annual ratio at that quantile as shown in worksheet “Steps 6 through 8”.

Step 8. Adjust Perturbed Flows to Match Annual Quantile Volume Ratios

Make a final adjustment to the total period of record volume such that the ratio of the perturbed gage-proration historical flow volume representing 2070 hydrology to gage-proration historical flow volume is equivalent to the ratio of VIC model 2070 to historical flow volume as shown in worksheet “Steps 6 through 8”.

A summary of the eight steps used to estimate future 2070 hydrology is shown in Figure C-9.

Figure C-9. Schematic of methodology used to develop projected flows.



Results

The results of the transformation method are demonstrated by the monthly flow distribution of gage-proration historical and perturbed gage-proration 2070 as compared to the linear transformed VIC model historical and 2070 flow distribution in Figure C-10. A comparison of the probability of exceedance of annual volumes is shown in Figure C-11. These figures illustrate how the bias correction methodology acts to adjust future flows based on the differences seen in the historical flows between the gage-proration and VIC models. For example, VIC model flow is underestimated relative to gage-proration flows in the month of May, and overestimated in the month of January. The perturbed gage-proration 2070 flows demonstrate the relative corrections to account for these biases. Figures C-12 and C-13 illustrate the effects of the bias correction methodology for the months of January and May, respectively, two of the months with the largest corrections.

Figure C-10. Comparison of monthly distribution of gage-proration and VIC model historical and 2070 flows in the Cisco sub-basin.

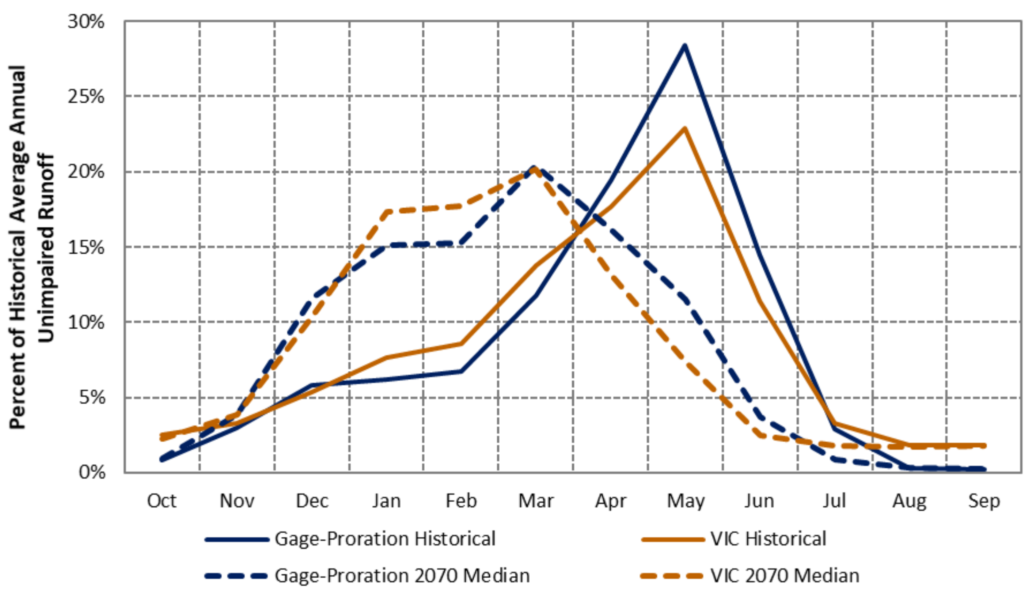


Figure C-11. Comparison of annual exceedance of gage-proration and VIC model historical and 2070 flows in the Cisco sub-basin.

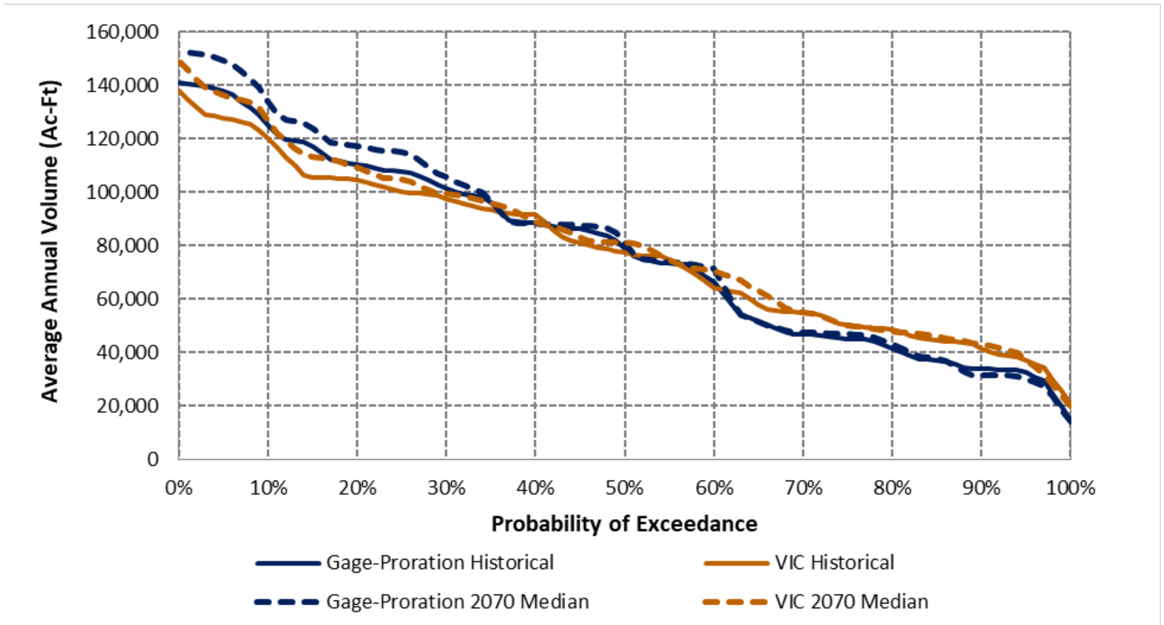


Figure C-12. Comparison of gage-proration and VIC model historical and 2070 flows for the month of January in the Cisco Sub-basin.

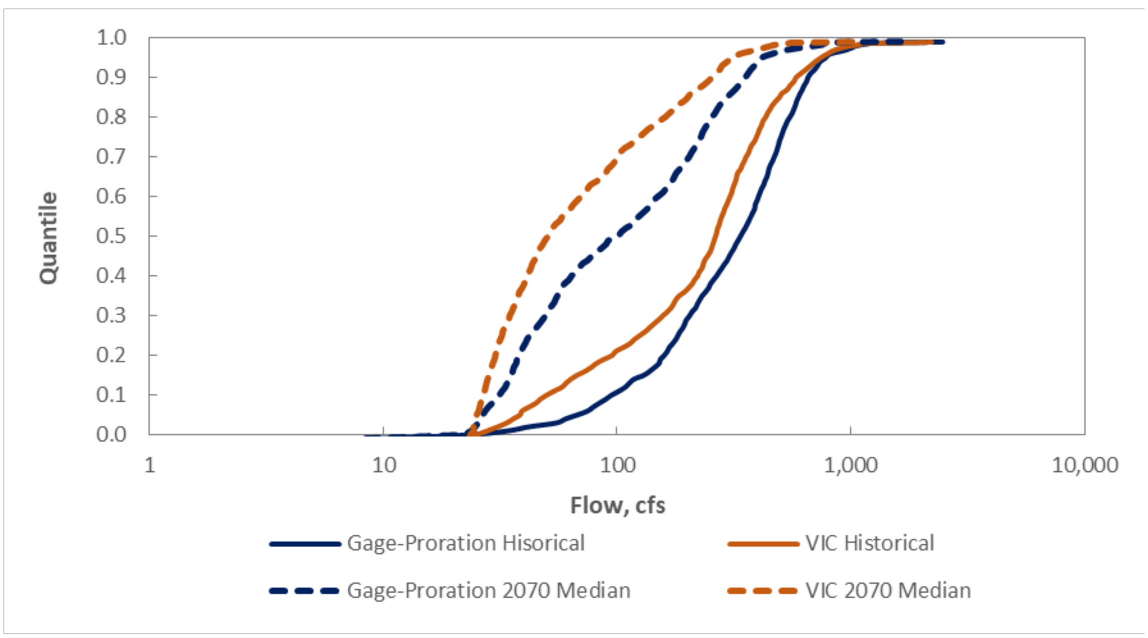
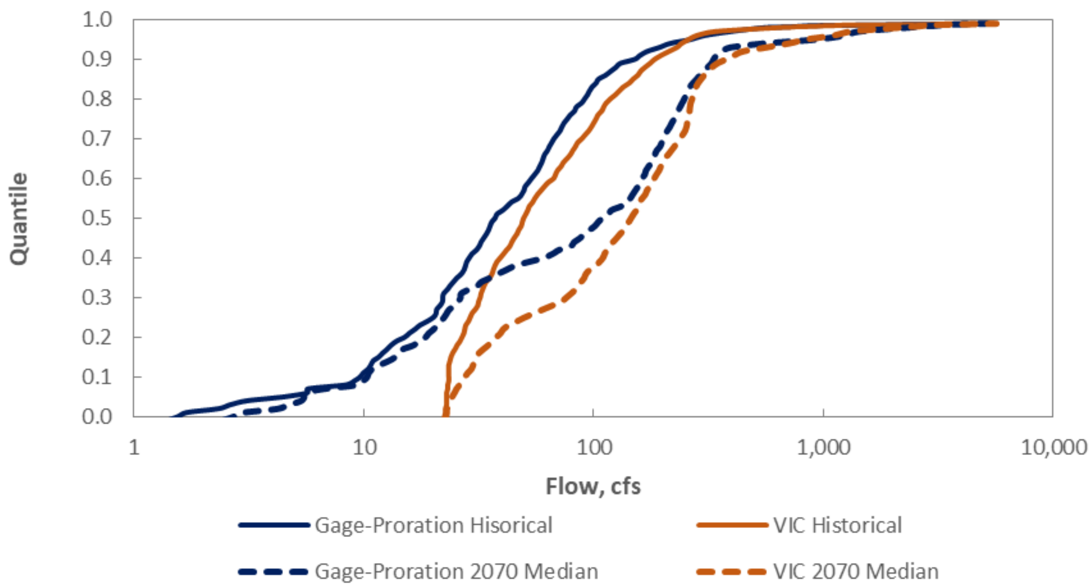


Figure C-13. Comparison of gage-proration and VIC model historical and 2070 flows for the month of May in the Cisco Sub-basin.



Summary

This appendix describes the applied methodology for estimating the 2070 unimpaired flows by applying perturbations to gage-proration historical flows. The perturbations are based on the quantile ratios of VIC model future to VIC model historical flows after correcting for biases between the gage-proration and VIC model hydrology. The transformed gage-proration historical flows are intended to represent potential future hydrology for each emissions scenario. Different methods of developing future flows may result in differences in temporal distributions and magnitudes of individual peak flows on a daily basis. However, general trends demonstrating changes in flow volume and relative monthly distributions are expected to be similar between methods.