Appendix B – Development of Historical Gage-Proration Unimpaired Hydrology

Introduction

The purpose of this appendix is to document the methods used to develop historical unimpaired hydrology. Unimpaired flow is defined as the hydrologic response of watershed basins with no influence (i.e., regulation) of stream flow by man-made structures such as dams or diversions. Quantification of unimpaired flow is important because it is used to estimate watershed runoff, required for understanding the timing and volume of water supply available to NID. Watersheds that contribute runoff to NID's water supply are either ungaged or highly regulated, or both. Because it is not possible to directly measure runoff in these watersheds it is necessary to synthesize unimpaired hydrology to quantify how much water is available to NID from runoff.

HDR first developed an unimpaired hydrology data set for Water Years[1] 1976 to 2008 during the joint FERC relicensing of NID's Yuba-Bear Hydroelectric Project and PG&E's Drum-Spaulding Project (Nevada Irrigation District 2012). These data sets have been updated and extended to include additional sub-basins and cover a longer period of record from Water Year 1976 through 2011. The lower bound of 1976 was chosen based on availability of stream gage data. The upper bound of 2011 is based on the available period of record of VIC model hydrologic data provided by the California Water Commission (CWC 2016) used for climate change assessments.

Gage Summation versus Gage Proration Methodology

This study applied two common approaches used to derive unimpaired hydrology in regulated watersheds: (1) gage summation using relevant stream and reservoir gages within the basin of interest, and (2) gage proration using data from nearby gaged reference basins with similar rainfall-runoff response to construct synthetic unimpaired hydrographs for the basin of interest.

The gage-summation method directly uses observed (i.e., gage) data to calculate unimpaired flow based on the regulated flow and storage data associated with man-made structures. For example, a reservoir will typically accumulate inflows during winter months and release outflows during summer months. This buffering of basin through-flow can be removed from the hydrograph using the daily change in reservoir storage in conjunction with reservoir discharge data to back calculate the unimpaired flow (Q_{inflow}) using the hydrologic water budget equation:

[1] Water years are defined as October 1 of the previous year through September 30 of the year documented.

$$\Delta S = Q_{inflow} - Q_{outflow} - Q_{losses}$$

Where: ΔS is the change in storage (cfs);
Q_{inflow} is the inflow (cfs);
$Q_{outflow}$ is the outflow (cfs); and
Q_{losses} is the sum of all losses, e.g. evaporation (cfs).

The gage-summation method also incorporates stream flow gage data from contributing drainage areas and accounts for losses from diversion flows.

The gage-summation method is subject to inaccuracies typically found in reservoir storage and stream flow gage data. A small error in reservoir elevation can result in a large error in calculated flow. Errors are evident in the summation data as negative inflows, as well as random or atypical hydrologic fluctuations. Accumulation of error from the gage data can render a significant portion of the synthesized daily unimpaired flow data to be unreliable. Also, data gaps in the gage record present a significant problem for use of the summation method.

A second approach, the gage-proration method (Mann et al 2004), characterizes unimpaired flows throughout a region of interest by utilizing flow data from a nearby unimpaired reference basin that has good gage data. The gage-proration method applied in this study gives an estimate of unimpaired flows for a given watershed of interest by scaling the reference basin's hydrograph as follows:

$$Q_{target} = \left(\frac{A_{target}}{A_{reference}}\right)\left(\frac{P_{target}}{P_{reference}}\right)Q_{reference}$$

Where: Q_{target} is the flow (cubic feet per second) for the sub-basin of interest;
$Q_{reference}$ is the flow (cubic feet per second) for the reference basin;
A_{target} is the drainage area (square miles) for the sub-basin of interest;
$A_{reference}$ is the drainage area (square miles) for the reference basin;
P_{target} is the mean annual precipitation (inches) for the sub-basin of interest; and
$P_{reference}$ is the mean annual precipitation (inches) for the reference basin.

Drainage areas were taken directly from USGS records where available, or by using Geographic Information System (GIS) data to delineate watersheds. Mean annual precipitation values were calculated using GIS to sum gridded mean-annual precipitation data published by the PRISM Climate Group (http://www.prism.oregonstate.edu/) for each basin.

Development of the FERC Relicensing Unimpaired Hydrology Dataset

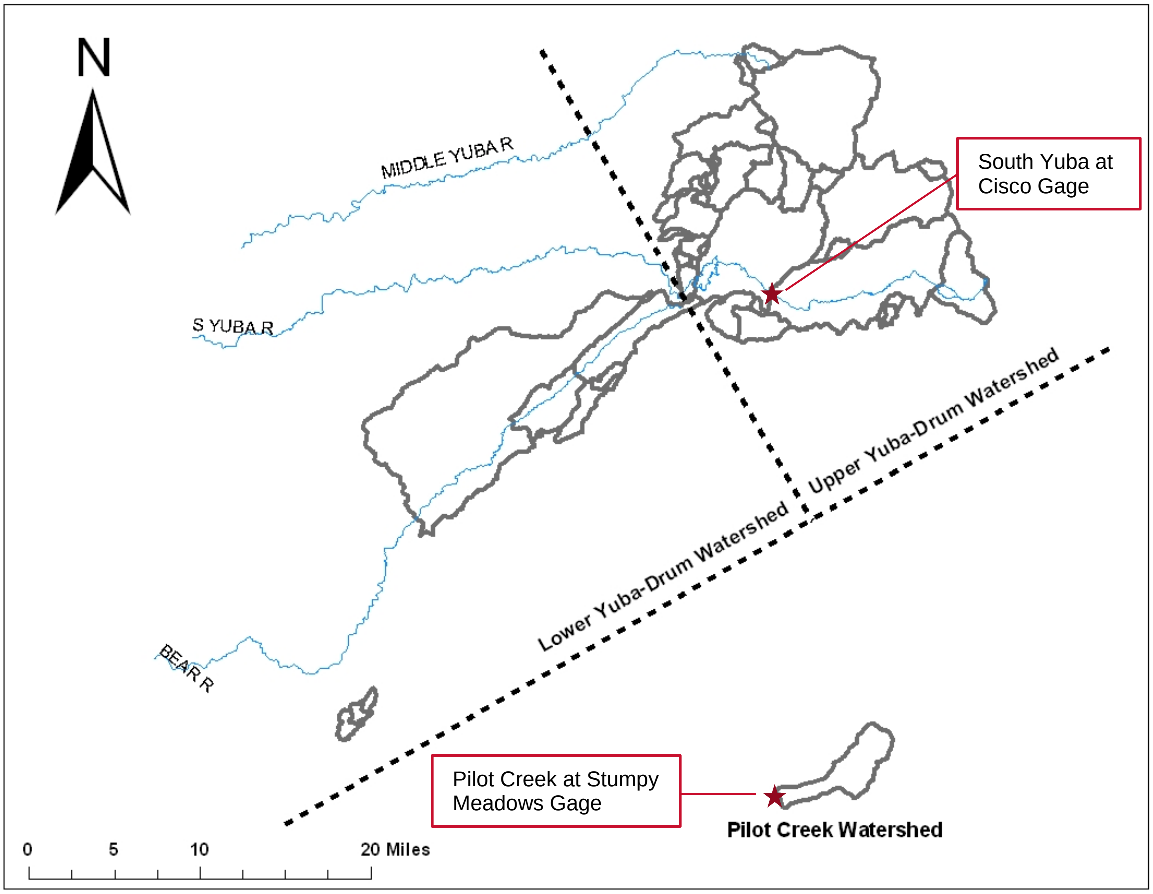
Unimpaired hydrology data were developed for the joint FERC relicensing of NID's Yuba-Bear Hydroelectric Project (FERC Project Number 2266) and PG&E's Drum-Spaulding Hydroelectric Project (FERC Project Number 2310). A report detailing the development of the unimpaired flow data can be found in Appendix E12 of Exhibit E of NID's application for a new FERC license (Devine Tarbell & Associates 2008). These data were accepted by FERC and other state and federal agencies to adequately represent historical unimpaired hydrology within the two hydroelectric project areas and were used during the relicensing process to evaluate impacts of potential operations and facilities modifications.

Gage summation was used as the initial approach for calculating unimpaired hydrology, However, during the development process it was determined that this method was not feasible for most of the sub-basins, primarily due to a lack of data for the full Period of Record (Water Years 1976 through 2008) at many locations (Devine Tarbell and Associates 2008). Therefore, two suitable reference basins were identified, one for basins with elevation greater than 5,000 feet and one for basins with elevation less than 5,000 feet, so that gage-proration could be utilized as a first step for synthesizing unimpaired flow data.

The South Yuba watershed above the stream gage at Cisco (USGS gage 11414000) was used as the gage-proration reference basin for high-elevation sub-basins (Upper Yuba-Drum Watershed) and the Pilot Creek watershed above Stumpy Meadows Reservoir stream gage (USGS gage 11431800) was used as the reference basin for low-elevation sub-basins (Lower Yuba-Drum Watershed). The distribution of high-elevation and low-elevation sub-basins is shown in Figure B-1. The South Yuba above Cisco location was selected as the reference basin because: 1) it is located within the Upper Yuba-Drum Watershed and is hydrologically similar to the other high-elevation sub-basins of interest; 2) it has very good data quality for the entire POR; and 3) its hydrology is largely unimpaired. The Pilot Creek watershed has good gage data with a full POR and its hydrology is completely unimpaired. Although the Pilot Creek sub-basin is located outside (to the south of) the Lower Yuba-Drum Watershed, it is representative of the lower-elevation sub-basins in terms of watershed setting, elevation, and shape.

The South Yuba at Cisco gage measures runoff from its entire watershed, which ranges in elevation from approximately 5,600 ft-msl at the gage to over 9,000 ft-msl at Castle Peak. To account for differences in elevation between other sub-basins in the Upper Yuba-Drum Watershed and the Cisco basin (both in range of elevations and percent of basin with a certain range of elevations), historical Cisco unit-area flow was parsed into discrete 1,000 ft elevation bands to be used as runoff spectrum for the other sub-basins based on their relative elevation ranges. Unique monthly average elevation corrections by elevation band were developed for each water year in the period of record using historical Cisco flow to distribute the relative runoff within each elevation band. Monthly flow errors were limited to no more than 2 percent for the entire Cisco basin within any given month. Utilization of unit-area flows by elevation band created more realistic seasonal unimpaired hydrographs, accounting for impacts of differing sub-basin elevation ranges on temporal runoff patterns from snowmelt.

Figure B-1. Map of the upper and lower basins, and the Pilot Creek reference basin.



Adequate gage data were available to calculate gage-summation unimpaired hydrology at 3 locations in the Upper Yuba-Drum watershed: the Middle Yuba at Milton Diversion Dam (Figure B-2), Canyon Creek at Bowman Dam (Figure B-3), and Fordyce Creek at Fordyce Dam (Figure B-4). The gage-summation hydrology was used to validate the gage-proration methodology using the Cisco watershed as a reference basin. Unimpaired flow data at Bowman Dam and Fordyce Dam compared well between methods. The comparison for Milton Diversion Dam, however, showed a distinct difference between the two methodologies. The difference was thought to be caused either by a faulty gage (or gages) in the Milton Diversion Dam sub-basin, or a poor matchup between the Cisco reference basin and the Middle Yuba River sub-basins being modeled. With input from FERC relicensing participants, monthly scaling factors were developed to adjust the gage-proration unimpaired hydrology based on comparison to gage-summation unimpaired hydrology. The average scaling factor for Water Years 1976 through 1986 is 0.75, and for Water Years 1987 through 2008 is 0.70.

Figure B-2. Comparison of Gage summation and gage proration unimpaired hydrology for the Middle Yuba River at Milton.

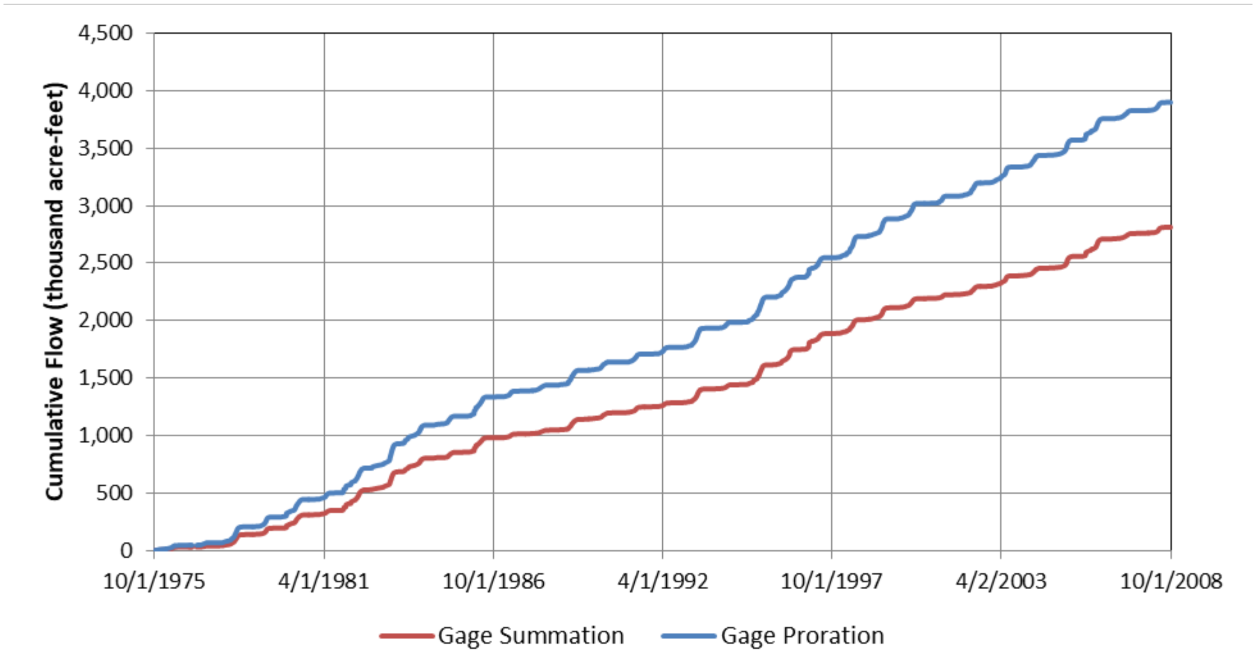


Figure B-3. Comparison of Gage summation and gage proration unimpaired hydrology for Canyon Creek at Bowman Dam.

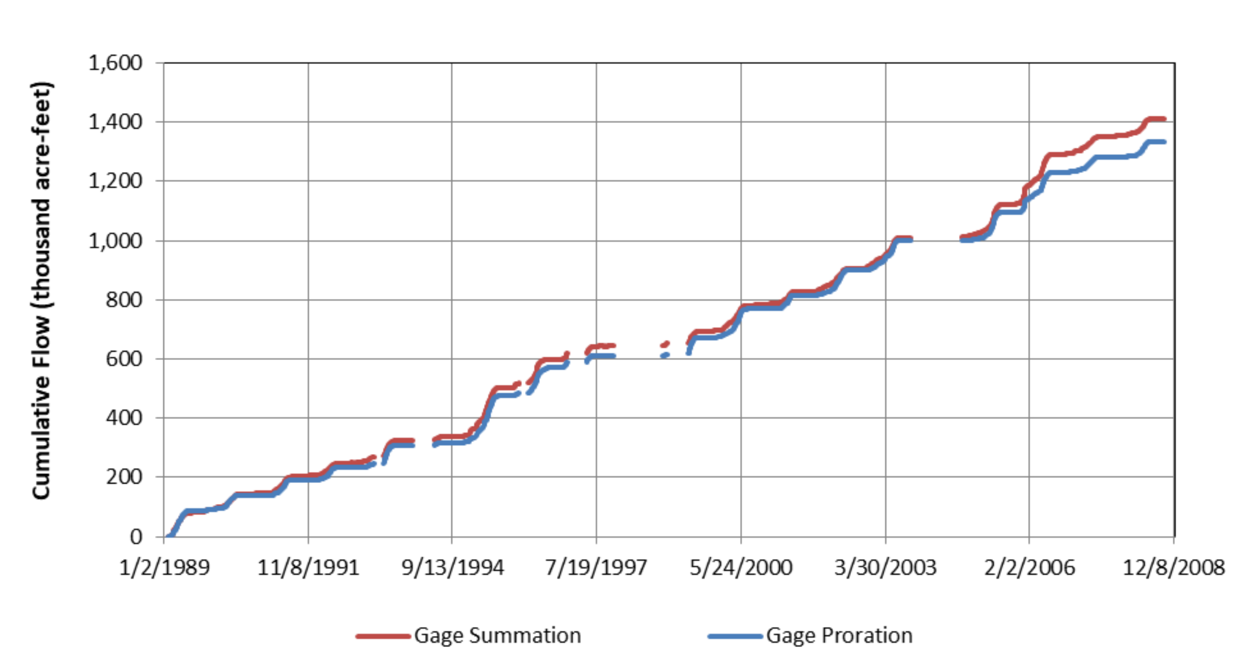
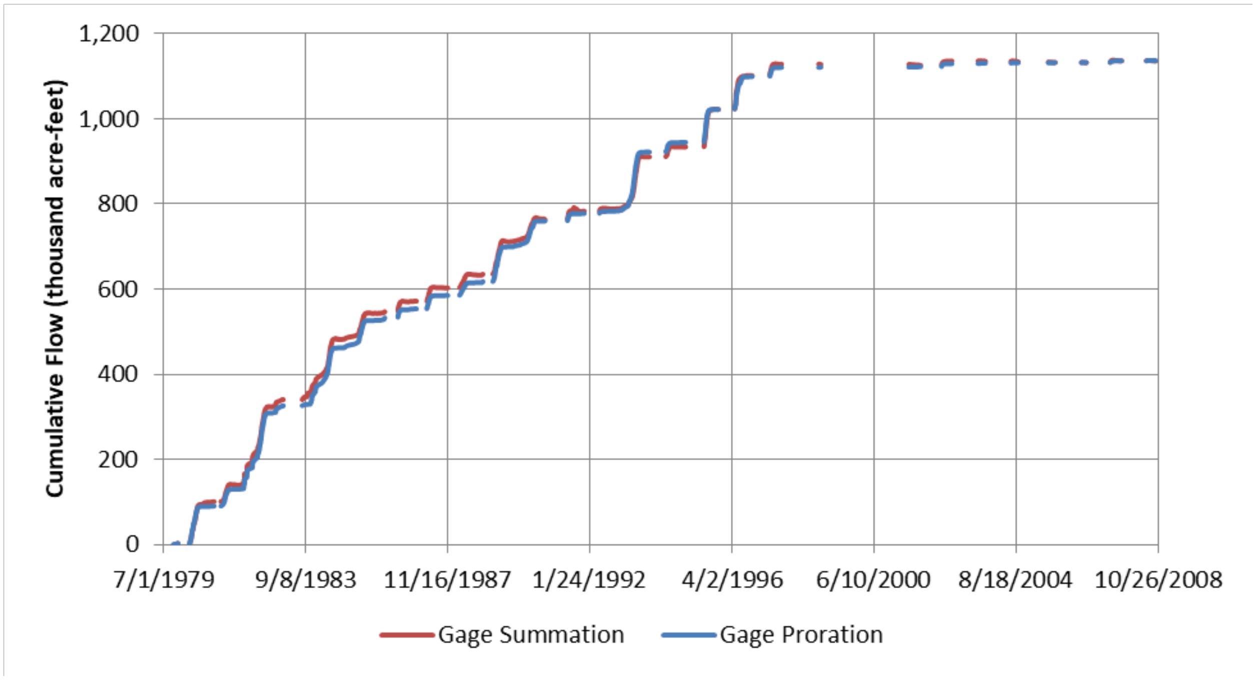


Figure B-4. Comparison of Gage summation and gage proration unimpaired hydrology for Fordyce Creek at Fordyce Dam.



Combined Gage-Proration Technique to Redevelop Low-Elevation Unimpaired Hydrology

The original FERC unimpaired hydrology data set does not cover all areas of the watershed where NID stores water, diverts water, or has water rights, as it only addressed sub-basins within the FERC project boundary. As part of this study, additional daily average unimpaired hydrology data were developed for sub-basins in:

- The Bear River downstream of the Bear River Canal and upstream of Camp Far West Dam;
- Deer Creek above Lake Wildwood Dam;
- Coon Creek downstream of Halsey Afterbay and Rock Creek Reservoir and above Camp Far West Canal; and
- Auburn Ravine above Hemphill Canal.

The additional watersheds include areas that are lower in elevation than sub-basins in the existing FERC unimpaired hydrology data set. For example, sub-basins in Auburn Ravine range in elevation from approximately 200 ft to 1,700 ft. Pilot Creek, the original reference gage for low-elevation sub-basins, is representative of mid-elevation watersheds (4,250 feet to 6,250 feet), but is not applicable to lower elevation watersheds because of differences in quantity and timing of snowmelt runoff contributions. Therefore, additional reference gages were compiled to better represent the extended elevation ranges, summarized in Table B-1. Figure B-5 is a location map showing the reference basins used.

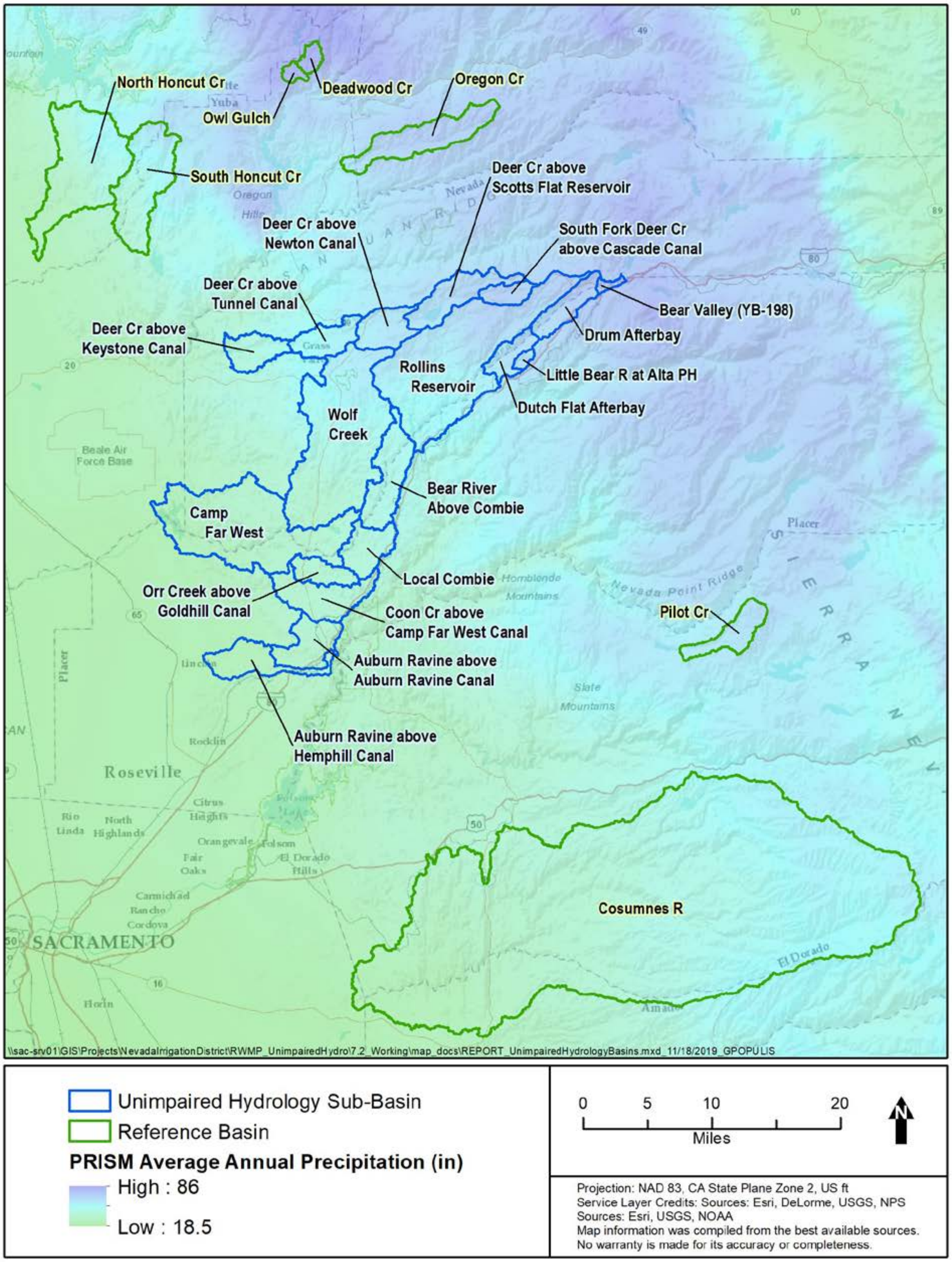
Table B-1. Reference gages used to develop unimpaired hydrology for low-elevation sub-basins.

Gage Name	USGS Gage Number	Start Date	End Date	Elevation Range (ft)	Drainage Area (mi^2)
Cosumnes River at Michigan Bar	11335000	10/1/1975	9/30/2011	250 – 7,500	534.6
Oregon Creek above Log Cabin Diversion	11409300	10/1/1975	9/30/2000	2,000 – 6,000	23.0
South Honcut Creek near Bangor	11407500 A05775 (DWR)	10/1/1975 7/6/2006	9/30/1986 9/30/2011	500 – 3,500	30.6
Pilot Creek above Stumpy Meadows	11431800	10/1/1975	9/30/2011	4,250 – 6,250	11.6
Deadwood Creek (sum)[1]	11413320[2] + 11413323[3] + 11413326[4]	10/1/1994	9/30/2011	3,000 – 4,000	5.0

[1] Water Years 2005 and 2006 are missing.
[2] Deadwood Creek near Strawberry Valley, CA.
[3] Owl Gulch near Strawberry Valley, CA.
[4] Deadwood Creek Power Plant near Strawberry Valley, CA.

Key: ft = feet mi^2 = square miles

Figure B-5. Map of reference basins used in unimpaired hydrology development and sub-basins (center of figure) where the reference basin data were applied.



The combined gage proration method subdivides both reference and target sub-basin areas into elevation bands and prorates the reference gage data by area and precipitation associated with each elevation band.

$$Q_{target} = \sum_j \left[\sum_i \left[Q_i \left(\frac{A_{ij} P_{ij}}{\sum_j A_{ij} P_{ij}} \right) \left(\frac{A_{tj} P_{tj}}{\sum_i A_{ij} P_{ij}} \right) \right] \right]$$

Where: Q_{target} is the flow (cubic feet per second) for the sub-basin of interest;
j refers to the elevation band
i refers to the reference basin
Q_i is the flow (cubic feet per second) for a reference basin;
A_{ij} is the drainage area (square miles) for the reference basin (i) and the elevation band (j);
P_{ij} is the mean annual precipitation (inches) for the reference basin (i) and the elevation band (j);
A_{tj} is the drainage area (square miles) for the elevation band (j) of sub-basin of interest; and
P_{tj} is the mean annual precipitation (inches) for the sub-basin of interest and the elevation band (j).

The combined gage proration method prorates gage data from multiple reference basins based on drainage area and average annual precipitation by 250 ft elevation bands. The benefits of using multiple reference gages to develop unimpaired hydrology include:

- Duplicate records allow coverage of reference gage data gaps.
- Inclusion of reference gages to the north and south of the target basins removes regional biases of individual reference basins.
- Reference gages can be selected based on similarities in watershed elevation ranges to the target sub-basin elevation range.
- Errors from individual gages are muted.

This method was used to develop unimpaired hydrology for the new sub-basins listed above, as well as to redevelop the unimpaired hydrology for all previous sub-basins in the Bear River watershed for consistency.

This combined gage proration approach was also used to develop unimpaired hydrology for Don Pedro Hydroelectric Project (FERC Project Number 2299) relicensing (Turlock Irrigation District and Modesto Irrigation District 2017).

Validation of the Combined Gage Proration Method

While the shape of a daily hydrograph is important for sub-daily operations decisions, reservoirs buffer their inflow making the shape less important than the overall inflow volume for studies of water supply in regulated watersheds. In the Bear River, Rollins Reservoir buffers both natural and imported flow. Combined gage-proration monthly inflow volumes to Rollins Reservoir were compared to reconstructed natural monthly inflow volumes to validate the combined gage proration technique.

Reconstruction of Rollins Reservoir Natural Inflow

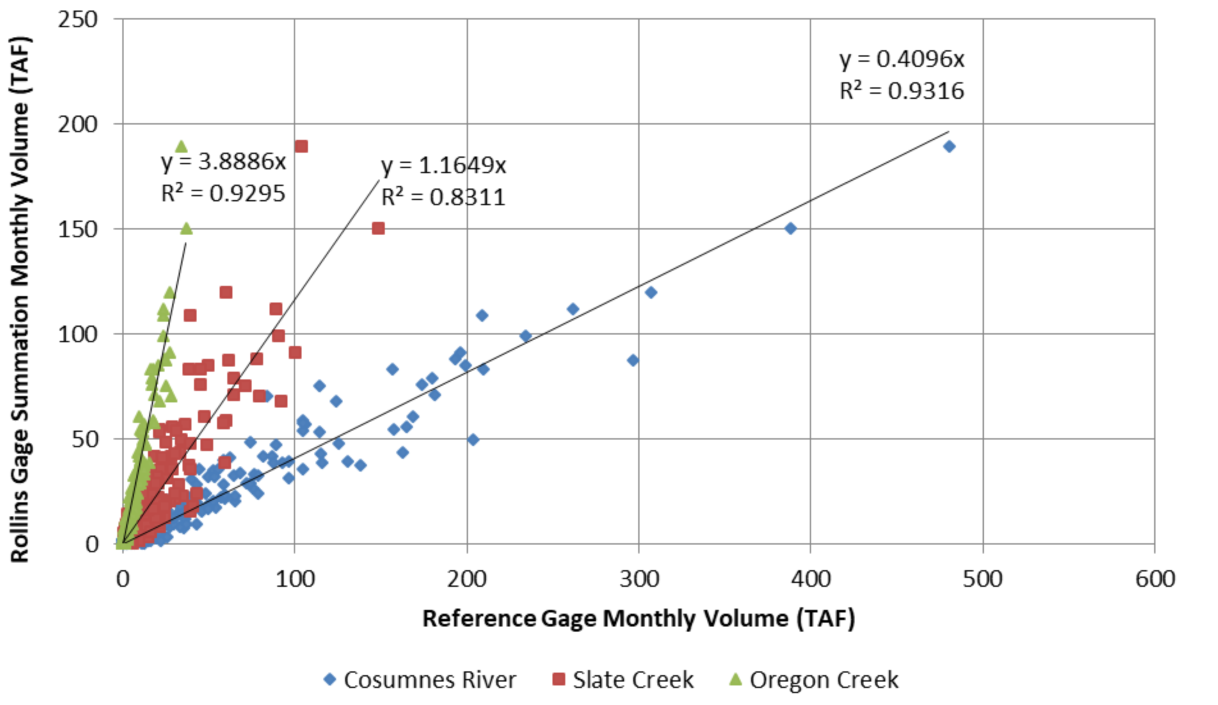
On a short-term (daily, weekly) basis, gage summation hydrographs are prone to error due to a number of factors, including missing data, poor data, intermittent data collection, measurement rounding, ungaged evaporation, canal leakage, and canal spillage. On a monthly basis, these errors are averaged out, but can still result in a poor representation of natural inflow.

Rollins Reservoir gage summation includes twelve gages in the Bear River basin. All twelve gages have a limited overlapping period of record, from October 1, 1992 to September 30, 2005. The Towle Diversion gage (PG&E gage YB-93), a critical gage used in the summation, had the shortest period of record. The following updates were made to minimize some of the known shortfalls of the historical gage record to improve and expand the gage summation period of record:

1. Towle Diversion (YB-93) flow was synthesized to estimate missing gage data. A regression equation was developed to estimate flow at YB-93 using gage records from January 2, 1993 through September 30, 2005 of inflow to Alta Forebay (YB-117), Canyon Creek below Towle Diversion (YB-282), and Canyon Creek above Towle Diversion (YB-280).
2. Gage records of imports to the Bear River from Drum Canal (YB-137) and South Yuba Canal (YB-139) waste gates are very poor. As an alternative, drainage-area-proration of Pilot Creek above Stumpy Meadows was used to synthesize the natural flow in the Bear River at Emigrant Gap (YB-198). Waste gate imports were calculated by subtracting the synthetic natural flow from YB-198 gaged flow.

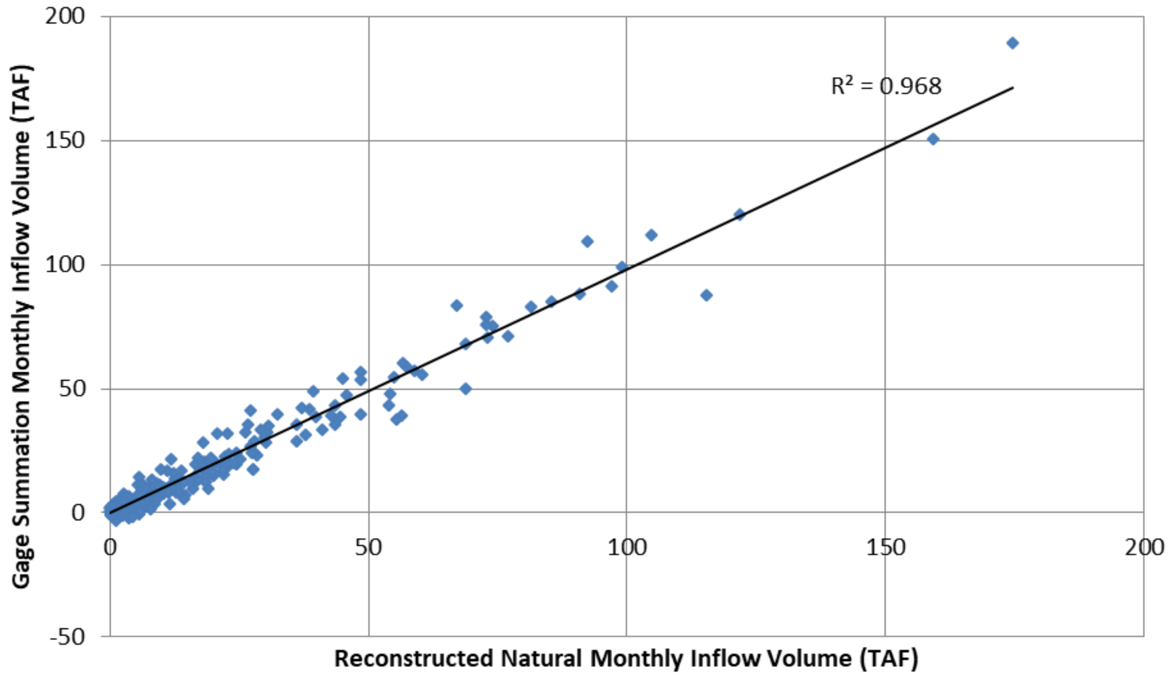
Gage summations were calculated daily and then averaged monthly. Even with the adjustments described above, there are some months when the calculated natural inflow to Rollins Reservoir was negative or unusually high. To smooth these data, a reconstruction of monthly Rollins Reservoir inflow volumes was created using linear regression of monthly volumes from three unimpaired USGS gages: Cosumnes River at Michigan Bar (USGS 11335000), Oregon Creek above Log Cabin (USGS 11409300), and Slate Creek above Diversion Dam (USGS 11413300+11413250). The Cosumnes River and Slate Creek basins both have a larger snowmelt component than the Bear River, so monthly multipliers were developed to reshape the gaged volumetric record. Figure B-6 shows the regressions used to reconstruct monthly natural inflow to Rollins Reservoir.

Figure B-6. Linear regressions of natural inflow to Rollins Reservoir from three unimpaired USGS gages.



There is some geographic variability in the amount of precipitation received during large storm events. This is why three gages were selected for this analysis, including one gage to the north (Slate Creek) and one to the south (Cosumnes River), relative to the low-elevation sub-basins for which unimpaired hydrology was being developed. An average of monthly volumes from the north and the south result in a better fit to Rollins Reservoir inflow than either the north or the south alone. Averages using the Cosumnes River and Oregon Creek regressions were used to reconstruct unimpaired inflow to Rollins Reservoir for Water Years 1976 through 2000. Averages using the Cosumnes River and Slate Creek regressions were used to reconstruct unimpaired inflow to Rollins Reservoir for Water Years 2001 through 2011. A comparison of the final reconstructed natural inflow to Rollins Reservoir compared to gage-summation inflow is shown in Figure B-7.

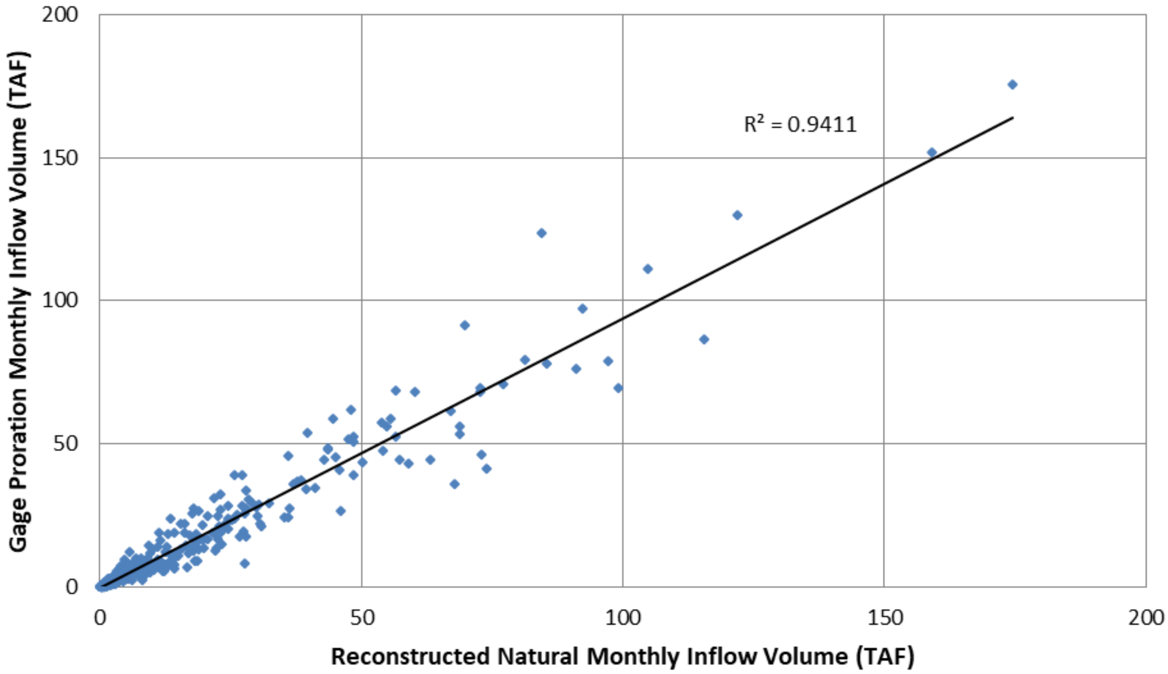
Figure B-7. Final reconstruction of monthly average natural inflow to Rollins Reservoir compared to monthly average gage summation inflow.



Validation Results

Gage-proration unimpaired hydrology for the Bear River above Rollins Reservoir was compared to the reconstructed natural monthly inflow to Rollins Reservoir to validate the combined gage proration technique, as shown in Figure B-8. Validation results show that unimpaired hydrology developed using the combined gage proration technique is able to reasonably represent reconstructed natural inflow to Rollins Reservoir. The combined gage proration technique was used to develop daily average unimpaired hydrology for all sub-basins in the Bear River, Deer Creek, Coon Creek, and Auburn Ravine watersheds.

Figure B-8. Results of gage proration monthly inflow volumes compared to reconstructed natural inflow to Rollins Reservoir.



Summary

Unimpaired hydrology is a fundamental input to NID's Operations Model, described in Section 4 of the Hydrologic Analysis Technical Memorandum. The historical unimpaired hydrology data set was developed to be compatible with the Operations Model's physical and temporal input requirements. Historical unimpaired hydrology was developed for 68 sub-basins in the Middle Yuba, South Yuba, Deer Creek, Bear River, Coon Creek, and Auburn Ravine watersheds for Water Years 1976 through 2011 using several methods.

A precipitation-weighted gage-proration method, using the South Yuba River at Cisco as a reference basin, was used to develop historical unimpaired hydrology for sub-basins in the Middle Yuba and South Yuba rivers, building on previously developed methods for FERC relicensing (Devine Tarbell & Associates 2008). The previous period of record (Water Years 1976 through 2008) for sub-basins in these watersheds was extended through Water Year 2011.

Combined gage proration, using a mix of low-elevation stream gages, was used to develop historical unimpaired hydrology for the remaining watersheds. Previously developed unimpaired hydrology for the Lower Yuba-Drum Watershed from the FERC relicensing was replaced with newly developed combined gage-proration unimpaired hydrology.

References

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