FROM DROUGHT TO FLOODS: A WATER BALANCE ANALYSIS OF THE TUOLUMNE RIVER BASIN DURING EXTREME CONDITIONS, 2015 – 2017

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EXTENDED ABSTRACT

The mountain snowpack responds in various ways to changes in precipitation and temperature regimes. Climate predictions overwhelmingly agree that temperatures will continue to rise, but future shifts in precipitation are more uncertain in the current literature (Luce et al., 2016). Regardless of future precipitation trends, winters are shortening and the likelihood of extreme events is increasing (Jentsch et al., 2007). One way to determine the effect of extreme events on water resources in snow-dominated catchments is to disaggregate the individual physical processes at work into the constituent components.

The water balance of a snow-dominated mountain basin is represented by three major components: precipitation (**P**), streamflow or runoff (**Q**), and the residual (**R**). Of these three terms precipitation is the most important in magnitude since it is the only input of water to the system and its uncertainty is usually the greatest in complex topography. However, the physical processes that make up the residual term are the least understood. The water balance residual is made up of evapotranspiration (**ET**) losses and groundwater fluxes (**ΔG**), the latter of which cannot be spatially resolved at this time due to the lack of understanding of subsurface processes. This study investigates the hypothesis that the residual term of the water balance of a snow-dominated mountain basin responds differently in years of varying water availability.

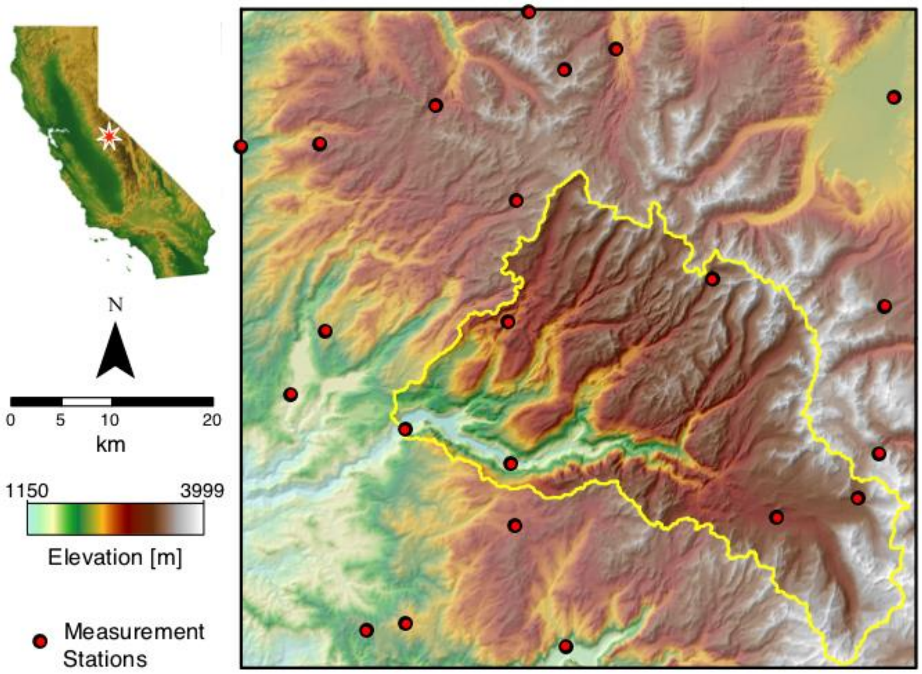

Figure 1. Location and relief map of the Tuolumne River Basin above Hetch Hetchy Reservoir within the U.S. State of California. Locations of various measurement stations used to force *iSnobal* in water year 2015 are depicted as red circles.

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Fortunately, between 2015 and 2017 California's Sierra Nevada underwent the largest dynamic range of snowpack conditions in recorded history. The winter of 2015 was the final year of the 2012-2015 California drought and it resulted in the lowest total April 1st snowpack in over 500 years according to tree ring snow water equivalent (SWE) reconstruction (Belmecheri et al., 2016). The following winter of 2016 resulted in a near-average snowpack, with April 1st totals around 85% of the recorded average. Lastly, the winter of 2017 resulted in the 2nd highest SWE on April 1 in recorded history, and the most reservoir inflow on record for many of the large reservoirs along the western slopes of the Sierra Nevada.

Our approach to investigating the water balance residual involves using a physically based, energy and mass balance snow model forced with gridded hourly meteorological estimates and occasional remote sensing measurements that update the model. The *iSnobal* snow model (Marks et al., 1999) has been tested extensively in previous studies (Erickson et al., 2005; Kormos et al., 2014; Reba et al., 2011; Winstral et al., 2013) and has been shown to produce accurate estimates of basin-averaged snowpack mass over annual timescales (Hedrick et al., 2018; Kormos et al., 2017).

In the Tuolumne River Basin (Figure 1), the NASA/Caltech Jet Propulsion Laboratory Airborne Snow Observatory (ASO) has performed snapshot lidar surveys throughout the ablation season since 2013 in order to determine the spatial distribution of snow depths (Painter et al., 2016). These snow depth snapshots are directly inserted into the *iSnobal* modeling stream to update the depth state variable. The modeled snow density and updated depths produce a spatially distributed SWE estimate over the basin on a daily basis at 50-meter resolution. In this snow-dominated basin (>80% of annual precipitation), the SWE distribution and subsequent modeled surface water input (SWI) are used as proxies for the precipitation input into the basin. Since the SWI is the product of the energy balance and high-resolution remote sensing measurements, the inputs are more accurate than other spatially gridded precipitation products.

The most well-constrained term of the water balance is Q and in the Tuolumne Basin this term is represented by the calculated full-natural flow (FNF) into the Hetch Hetchy Reservoir. Estimates of cumulative FNF since 1970 and the mean value since 1919 are shown in Figure 2. For the three years considered in this study, the large dynamic range of streamflow magnitudes is evident.

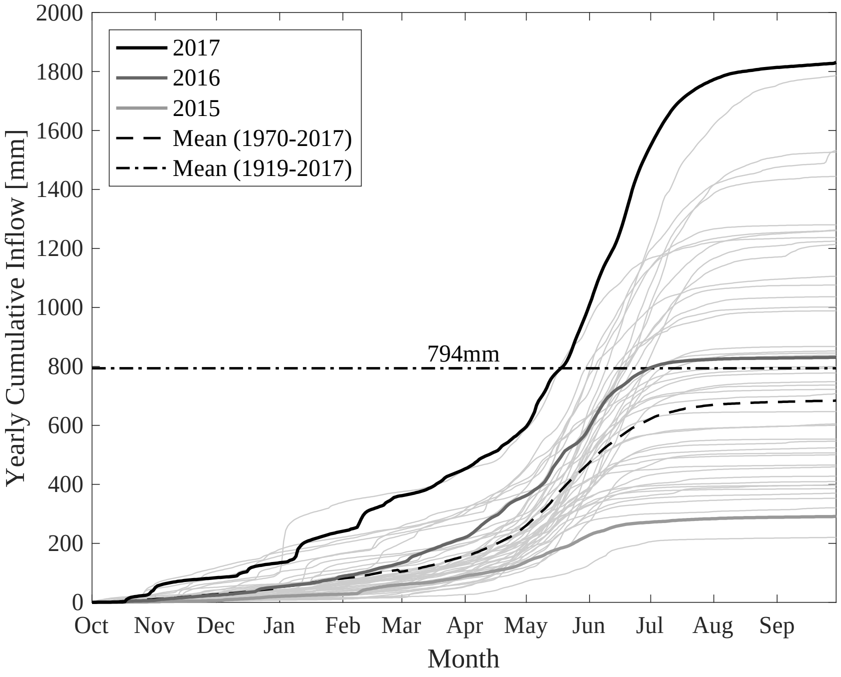

Figure 2. Cumulative estimated daily FNF into Hetch Hetchy Reservoir. Daily measurements began in 1970, but mean values from 1919 – 1970 were kept by hand and the mean inflow since the dam construction is shown as the horizontal line.

Previous work has examined ET amounts in the Sierra Nevada using water balance approaches (Henn et al., 2018) and regressions between eddy flux tower measurements and satellite products (Fellows and Goulden, 2016; Goulden et al., 2012). These approaches focused on different applications but concluded that annual ET in the upper elevations of the Sierra Nevada ranged between 150mm and 400mm with the majority of the losses occurring below treeline. In the Tuolumne Basin, approximately 50% of the land area is above treeline and is heavily snow-dominated, shortening the annual duration when ET can occur. Therefore, the actual ET in the basin is most likely toward the lower end of the estimates from the literature. Storage fluxes within the basin are not well known and are considered to be negligible in this study. Further work is required to quantify these fluxes in this basin.

Accurate spatial representations of the remaining water balance term, P, are problematic (Livneh et al., 2014). Figure 3 depicts the results of two methods for deriving gridded precipitation data. Figure 3a depicts the 2016 annual cumulative precipitation at 50-meter resolution from a detrended kriging (DK) distribution method (Garen et al., 1994). The DK distribution is derived from station measurements and is representative of both local elevation gradients and larger scale rain shadow effects. Figure 3b shows the cumulative precipitation for the same year at 4-kilometer resolution estimated by the Precipitation-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 1994). Within the Tuolumne Basin the difference between the two methods is just over 1% of the annual total precipitation, yet the spatial structure of where precipitation falls is much more defined by the DK method.

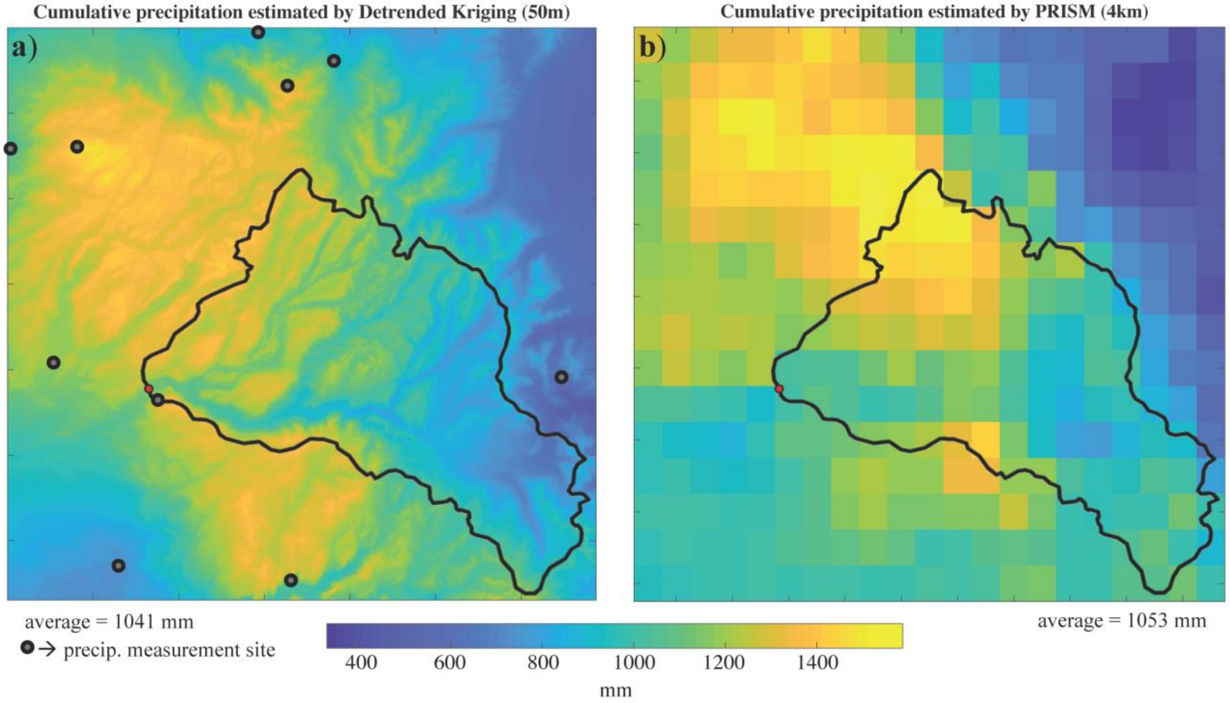

Figure 3. Cumulative precipitation from (a) station measurements of precipitation interpolated to a 50m grid using detrended kriging and (b) the 4km PRISM product for water year 2016. Locations of stations used by the DK method are depicted as circles in (a).

Prior to the first ASO update to the model, *iSnobal* is forced with DK precipitation grids and therefore results in a more uniform modeled SWE estimate. At the time of the first update, the resulting snow distribution is redefined and SWE is altered throughout the basin. The spatial structure of the ASO-defined distribution is maintained throughout the rest of the year and benefits from each subsequent ASO update. For water years 2015 through 2017, *iSnobal* was run with and without the ASO updates to demonstrate the basin-averaged impact of redefining the snow distribution (Figure 4).

In water years 2015 and 2016 the total SWI from the base of the snowpack was not sensitive to the redistribution of the snowpack from the ASO updates, though importantly the timing of that input pulse to the system was advanced by 2 to 4 weeks during the timing of peak streamflow in 2015. However, 2017 proved to be a difficult year for running *iSnobal* in the Tuolumne Basin. The main reason was a lack of precipitation station data at higher elevations. The first ASO update of 2017 had a minor effect on the basin SWE storage signifying that the modeled input mass was accurate prior to February. However, the second update added approximately 20% of SWE storage to the basin. This was because the higher sites in the modeling domain became covered with snow during the February storms and an accurate elevational gradient in the DK product could not be resolved. Further work will investigate methods for better estimating precipitation inputs to the basin without relying on station measurements alone. These would not be limited to using a meteorological forecasting model such as the Weather Research Forecast (WRF) model or the High-Resolution Rapid Refresh (HRRR) model for forcing inputs. Currently disregarding 2017, the residuals in 2015 and 2016 agree with the findings of Henn et al. (2018), which estimated the residual for 2013 to 2015 to be between 118mm and 231mm. This result of our approach is encouraging for estimating ET from this water balance approach. (KEYWORDS: water balance, drought, iSnobal, ASO, Tuolumne)

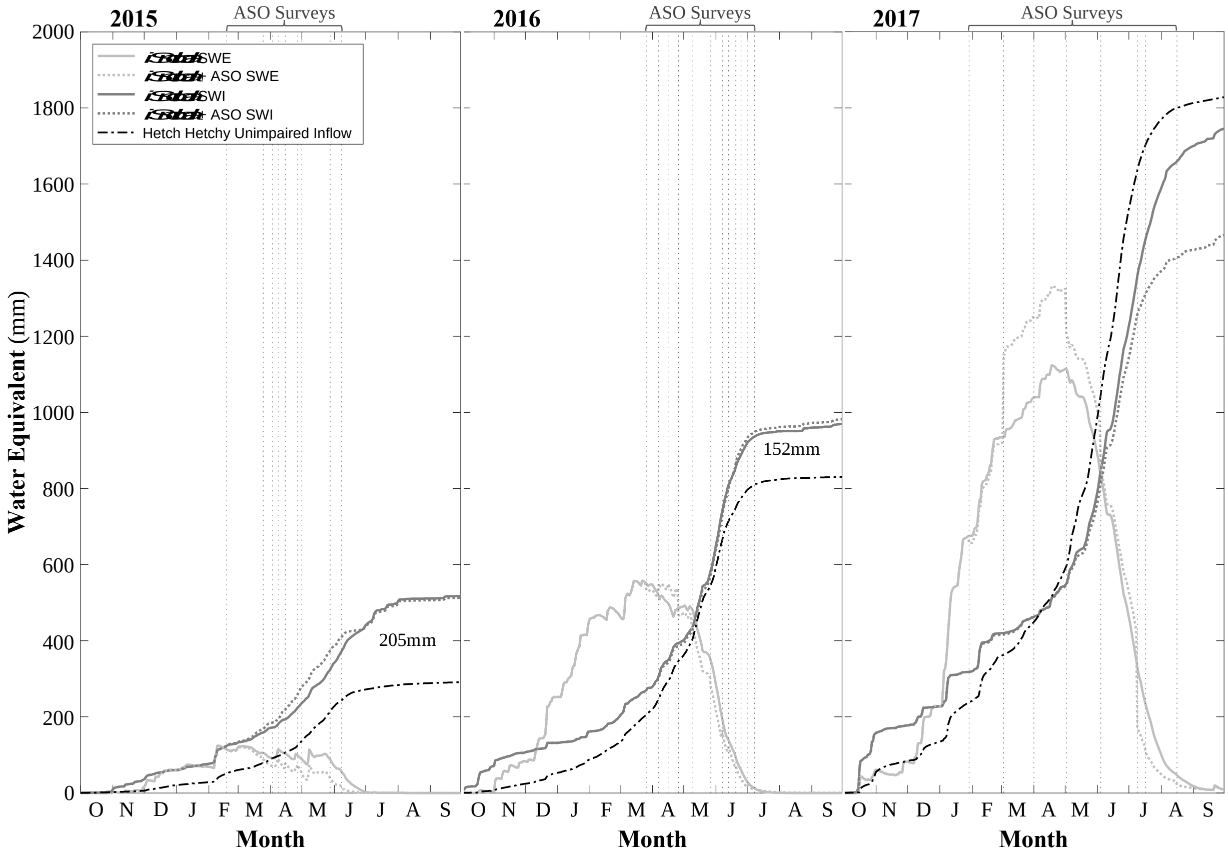

Figure 4. Basin-averaged totals of estimated SWE, cumulative estimated SWI, and cumulative inflow to Hetch Hetchy Reservoir for water years 2015–2017. Dates of ASO surveys are shown as vertical dashed lines. Reservoir inflow was provided by Hetch Hetchy Water and Power.

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