Big Creek Water Balance: Summary Report

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1 Introduction and Background

As the percentage of electricity that is supplied by solar power grows on the grid, there grows an increasing mismatch between when energy is produced and when it is needed. Energy storage is one solution to this problem, but massive amounts of energy would be needed to support a high penetration of solar power onto the grid. For California, several studies have explored the possibility of solar power supplying 50% or more of California's electricity [1, 2], and have concluded that between 150-250GWh of energy storage would be required. Pumped storage is one potential solution to this challenge, but environmental motivations and site limitations prevent new dams from being built which may help to supply this storage. Converting existing hydropower facilities to be used for massive pumped hydro storage could provide the benefits of energy storage without the negative environmental costs of new dams.

This report presents a monthly water balance for the six reservoirs in the Big Creek System, a hydropower facility in the Upper San Joaquin watershed in Central California. The watershed, approximately 4000km^2, varies in elevation from 90m to 4000m, with the reservoirs themselves between 400m and 2300m. These six reservoirs–Thomas A. Edison Lake, Florence Lake, Mammoth Pool Reservoir, Huntington Lake, Shaver Lake, and Redinger Lake–combined with their powerhouses produce about 1000MW of dependable power to the electric grid in California. An average of 2km^3 of runoff flows through the system each year, although year-to-year values deviate far from this mean, as over 50% of years are either critically dry or wet. Most of this runoff occurs in May to July in the form of snow melt. Summer storms account for only about 3% of precipitation [3].

The goals of this report are to (1) understand current water management, including the main fluxes throughout the system and how these fluxes change seasonally, and (2) estimate evaporation and groundwater seepage losses, if possible. Section 2 details the methods and data that were used to conduct the water balance, while section 3 presents the results.

2 Methods

We performed monthly and yearly water balances for each of the 6 reservoirs in the Upper San Joaquin watershed using a standard conservation of mass equation:

$$\frac{dS}{dt} = I + P - O - \epsilon$$

where

- $\frac{dS}{dt}$ is the change in storage of the reservoir over the time period
- I is the inflow from rivers or diversions
- P is the direct precipitation onto the reservoir
- O is the outflow to rivers downstream, or diversions e.g. to powerhouses or other reservoirs
- ϵ is the resulting error, and is expressed as a negative to highlight the fact that this term encapsulates both evaporation and seepage losses from the reservoir

Table 1: Analysis periods chosen for each reservoir.

Reservoir Name	Analysis Period
Edison	1954-2016
Florence	1925-1980
Mammoth	1980-2016
Huntington	1986-2016
Shaver	1989-2016
Redinger	1986-2016

Table 2: NOAA weather stations used

Station Name	Station Number	Period of Record	Notes
Auberry 2 NW, CA US	USC00040379	1915/07/27 to 2017/09/30	Used at Redinger.
Big Creek Powerhouse 1, CA US	USC00044176	1915/06/01 to 2017/12/08	Used at Shaver. Gap in data between 1989 and 1999.
Huntington Lake, CA US	USC00044176	1915/06/01 to 2011/12/08	Used at Shaver and Huntington

2.1 Data and Period Analyzed

Southern California Edison, the operator of these reservoirs, has a long, consistent record of reservoir storage, dating back as far as 1925 for some of the older reservoirs. Outflows were in general well provided by stream gages, although a key outflow from Huntington Lake was lacking from 1986-2015. Precipitation was estimated using either NOAA station data [4, 5] where available for the entire period, or the CRU 4.1 dataset [6, 7], a gridded dataset from 1901-2016 based on observations. See Tables 2 and 3 for the list of gages and weather stations used (Table 3 is located in the Appendix).

While inputs from diversions were well-accounted for by USGS stream gages, river inflows were typically minimal or nonexistent, except in the case of powerhouses that flowed into reservoirs. An area based method was used to estimate inflows, described in Section 2.2. This estimation includes overland flow on regions near the reservoirs that would flow into them directly, without first reaching a river channel.

The periods analyzed were guided primarily by where outflow data was available. See Table 1 for a summary of analysis periods for each reservoir. Most reservoirs had good records extending from the mid 80s to September 30th, 2016, the end of the 2016 water year. Because one of the primary goals of this analysis was to understand current water management, I focused on this time period. The notable exception to this was Florence Lake, as its downstream gage on the South Fork San Joaquin River was discontinued in 1980. I therefore chose to conduct a water balance on Florence when this gage was in use, from 1925 to 1980.

2.2 Estimating Inflows Using The Area Method

Most or all of the inflows lacked stream gages for the periods analyzed. To overcome this, I used an area-based method, where the inflow is estimated by using a ratio between the watershed of the desired point and a reference gage:

$$Q_{point} = Q_{reference} * \frac{A_{point}}{A_{reference}}$$

This method is often used in hydrology to estimate gage data [8], and was used by Southern California Edison's Combined Aquatics Working Group (CAWG) during their relicensing process in the early 2000s to estimate unimpaired inflows [3]. In addition to the precedent established by the CAWG, we chose this method because of its ability to account for snow melt timing and conversion to discharge, assuming the reference gage has similar precipitation rates and temperature to the watershed of the desired point.

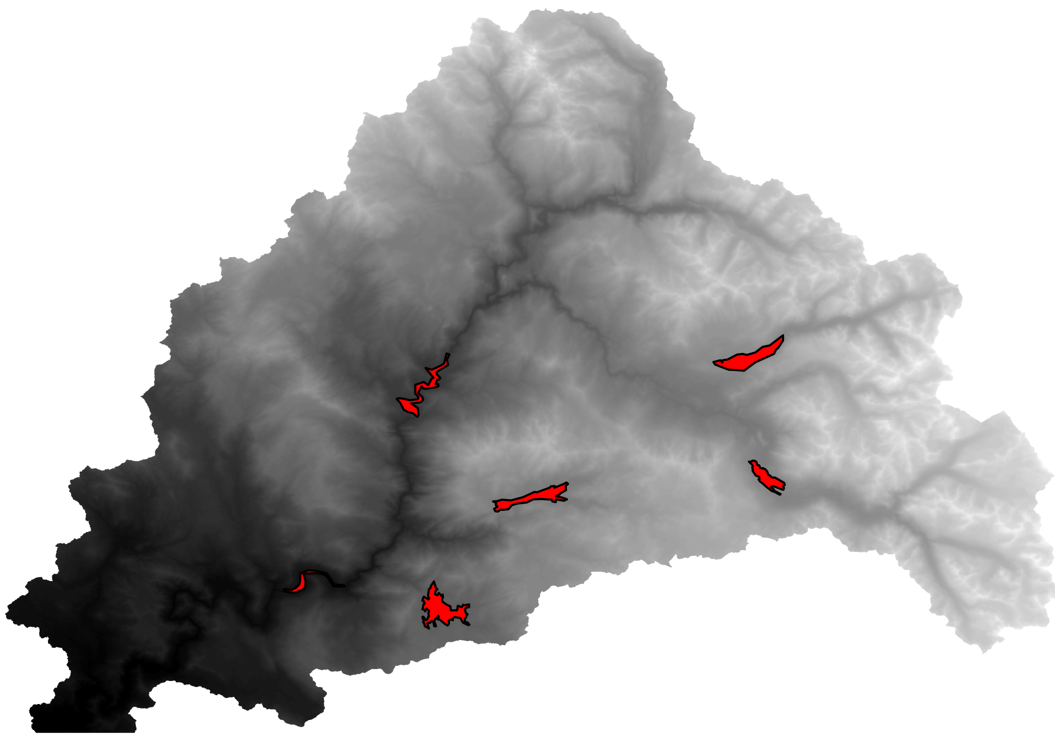

Figure 1: USGS elevation data for the Upper San Joaquin Watershed [9], where black represents low elevation (min = 91m) and white high elevation (max = 4349m). Reservoirs are shown in red. Kaiser ridge, the white streak in the center of the figure separating the left 4 reservoirs from the right 2, casts a rain shadow, doubling the precipitation on its west slopes compared to its east[10].

Watersheds were computed in ArcGIS using elevation data from the USGS [9] at a 1/3rd arc second (10m) resolution (see Figure 2.2 for elevation data). First, sinks were filled to ensure a sensible stream network was calculated. A flow direction raster was generated using a steepest descent algorithm, giving the direction of flow from each pixel. A flow accumulation raster was then produced to estimate the contributing area to any point in the stream channel. 24 stream gages and 6 reservoirs were overlaid on the stream channel, and their watersheds determined using the flow direction and flow accumulation rasters.

Figure 2.2 shows the watersheds of the 6 reservoirs, along with those of Pitman Creek (west, green) and Bear Creek (east, green). Pitman Creek and Bear Creek were selected as reference watersheds because they are the only two gages with unimpaired watersheds and consistent data during the period of analysis. Edison and Florence used Bear Creek, while Shaver, Huntington, and Redinger used Pitman Creek as their references.

For Mammoth Pool, using just one reference gage proved ineffective. Instead, in line with [3], we used Bear Creek as a reference gage for 1126km^2 of Mammoth's watershed and Pitman Creek for the other 1476km^2. The physical argument for this is two fold. The first is one of elevation. Bear Creek's watershed lies mainly between 3000-4000m, while Pitman Creek's sits between 2000-3000m. Mammoth Pool's watershed has significant portions at both of these elevations and these changes in elevation affect snow melting patterns. The second lies in the existence of Kaiser Ridge, a 3000m ridge that separates Florence and Edison from Mammoth and Huntington. This ridge creates a rain shadow, causing storms approaching from the west to dump most of their precipitation on the west slopes [10]. Pitman Creek, like a portion of Mammoth Pool's watershed, lies to the west of Kaiser Ridge, while Bear Creek lies to the east.

2.3 Specific Reservoir Equations

This section defines the specific gages and equations that were used for each reservoir. They are written to solve for ϵ, as this was the only unknown term after inflows were estimated. Many inflows were estimated using an area-based method (see section 2.2).

USGS gages and NOAA stations are referred to by their site number. Precipitation estimates using CRU data are denoted as P_{CRU}. The reservoirs Edison, Florence, Mammoth, Huntington, Shaver, and Redinger are denoted by the first letter of their name in the subscript. For changes in storage, changes were first calculated on a daily basis, and then on a monthly or yearly as required.

2.3.1 Edison

$$\epsilon_E = I_{est,E} + P_{CRU,E} - USGS_{11231500} - \frac{dS_E}{dt}$$

$I_{est,E}$ was estimated using the Bear Creek gage (site number 11230500).

2.3.2 Florence

$$\epsilon_F = I_{est,F} + P_{CRU,F} - USGS_{11230000} - USGS_{11229500} - \frac{dS_F}{dt}$$

$I_{est,F}$ was estimated using the Bear Creek gage (site number 11230500).

2.3.3 Mammoth Pool

$$\epsilon_M = I_{est,M} + P_{CRU,M} - USGS_{11235100} - USGS_{11234760} - \frac{dS_M}{dt}$$

$I_{est,M}$ was estimated using both the Bear Creek gage (site number 11230500) and the Pitman Creek gage (site number 11237500). See section 2.2 for details.

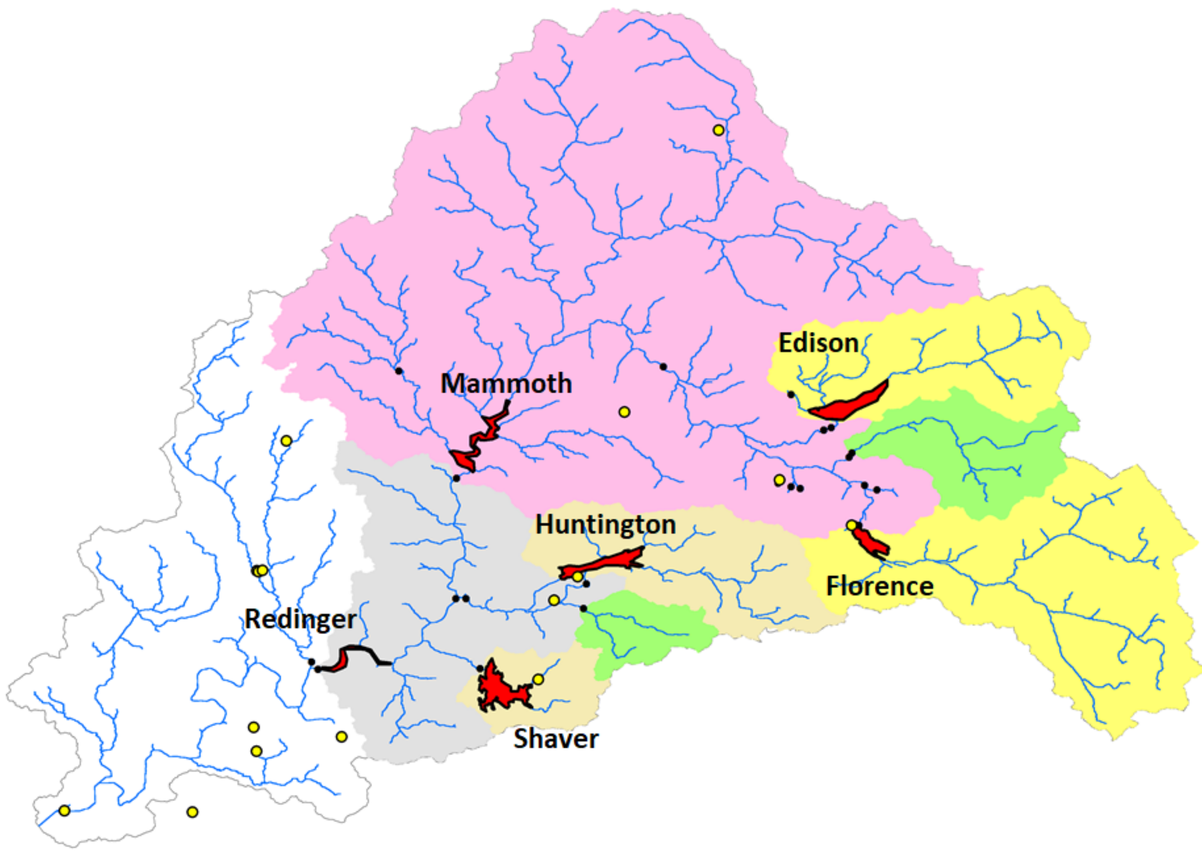

Figure 2: Watersheds of the 6 main reservoirs and the 2 reference gages used to estimate inflows (green). Note that Mammoth's watershed (pink) is overlapped by Edison, Florence, and Bear Creek (northwest, green), while Redinger's watershed (gray) is overlapped by every other watershed shown.

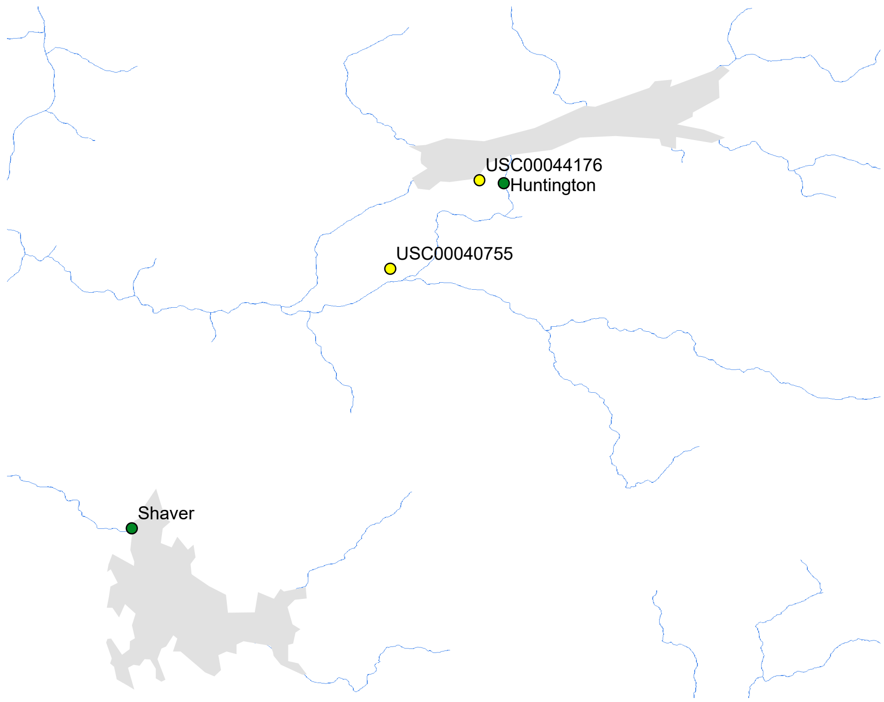

Figure 3: NOAA stations used to estimate precipitation at Shaver Lake and Huntington. The distance from Shaver to the nearest gage is approximately 10km.

2.3.4 Huntington

$$\epsilon_H = I_{est,M} + USGS_{11235500} + NOAA_{USC00044176} \\ - USGS_{11238100} - USGS_{11237000} - (USGS_{11238250} - USGS_{11237600}) - \frac{dS_H}{dt} \quad (1)$$

$I_{est,H}$ was estimated using the Pitman Creek gage (site number 11230500), as the input gage used is a diversion carrying water from Florence and Edison, but does not include water from Huntington's own watershed. The NOAA station was located next to the lake. Outflows through the Huntington-Pitman-Shaver conduit, which supply the majority of water to Shaver Lake, were not measured during the time period analyzed (1986-2016), and were estimated by subtracting the difference of flows at Eastwood Powerhouse (USGS 11238250) and North Fork Stevensen Creek Diversion (USGS 11237600).

2.3.5 Shaver

$$\epsilon_S = I_{est,S} + USGS_{11239300} + USGS_{11238250} + NOAA_{multiple} \\ - USGS_{11238400} - USGS_{11241500} - \frac{dS_S}{dt} \quad (2)$$

$I_{est,S}$ was estimated using the Pitman Creek gage (site number 11230500), to estimate the contribution of approximately 25km^2 that were not accounted for using the other two input gages. Two NOAA stations were used to estimate precipitation. The first and closest (USC00040755) was used from 1999-02-01 to 2010-04-30, the entire period for which it had data in our analysis period. When required to fill in the analysis period (1989-2016), the farther station was used (USC00044176).

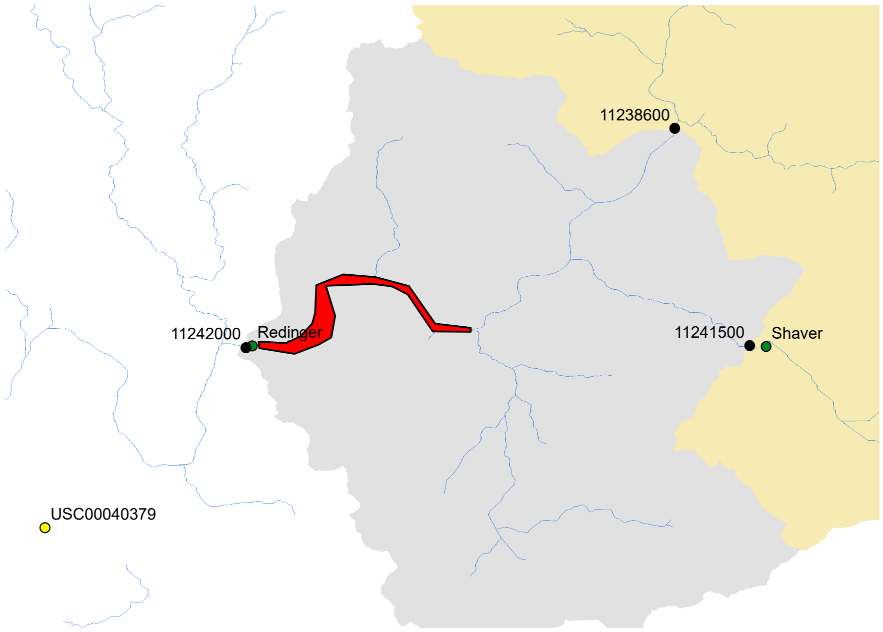

Figure 4: Stream gages (black) and weather station (yellow) stations used at Rediner Lake. Powerhouse gages are not shown. Note the portion of the watershed shown in gray not covered by any stream gage.

2.3.6 Redinger

$$\epsilon_R = I_{est,R} + USGS_{11241800} + USGS_{11238600} + USGS_{11241500} + NOAA_{USC00040379} - USGS_{11246530} - USGS_{11242000} - \frac{dS_R}{dt} \quad (3)$$

$I_{est,R}$ was estimated using the Pitman Creek gage (site number 11230500), to estimate the contribution of roughly 220km^2 that were not accounted for using the other two input gages (Figure 4). The NOAA station was located outside of Auberry California at a distance of approximately 9km.

3 Results and Discussion

Figures 5 through 11 show the monthly means of the fluxes in and out of each reservoir over the analysis period. One can see that the area-based method for estimating inflows was largely effective in representing the seasonal cycle of inflows, but had a tendency to underestimate magnitude. It proved most effective at Edison (Figure 5) and Florence (Figure 6), regions close to and of similar elevation and area to Bear Creek. At Mammoth Pool, the inflow estimation produced a peak in the error in May, followed by consistent underestimation of inflows throughout the rest of the year. This performance still exceeded an attempt that just used the Bear Creek watershed as a reference, which shifted the inflow peak to June and July when the outflows were already decreasing (see Appendix, Figure 12).

The underestimation of inflows makes it difficult to estimate evaporation using the water balance approach taken. However, it is likely that evaporation plays a small role in this system. Figure 8 shows the monthly water balance for Shaver Lake, with CRU potential evaporation estimates in red. Shaver Lake is the only reservoir for which error is always positive, which is what we would expect if inflows have been correctly estimated. Even so, evaporation accounts for only a small portion of the error. The rest may be accounted for by gaps or errors in the data. Figure 17 shows a yearly water balance for Shaver, where spikes in the error can be attributed to abnormal lows in the output data.

While data for outflows was in general readily available, this was not the case at Huntington Lake. The Huntington-Pitman-Shaver conduit brings most of the flow that enters Shaver Lake. It receives water

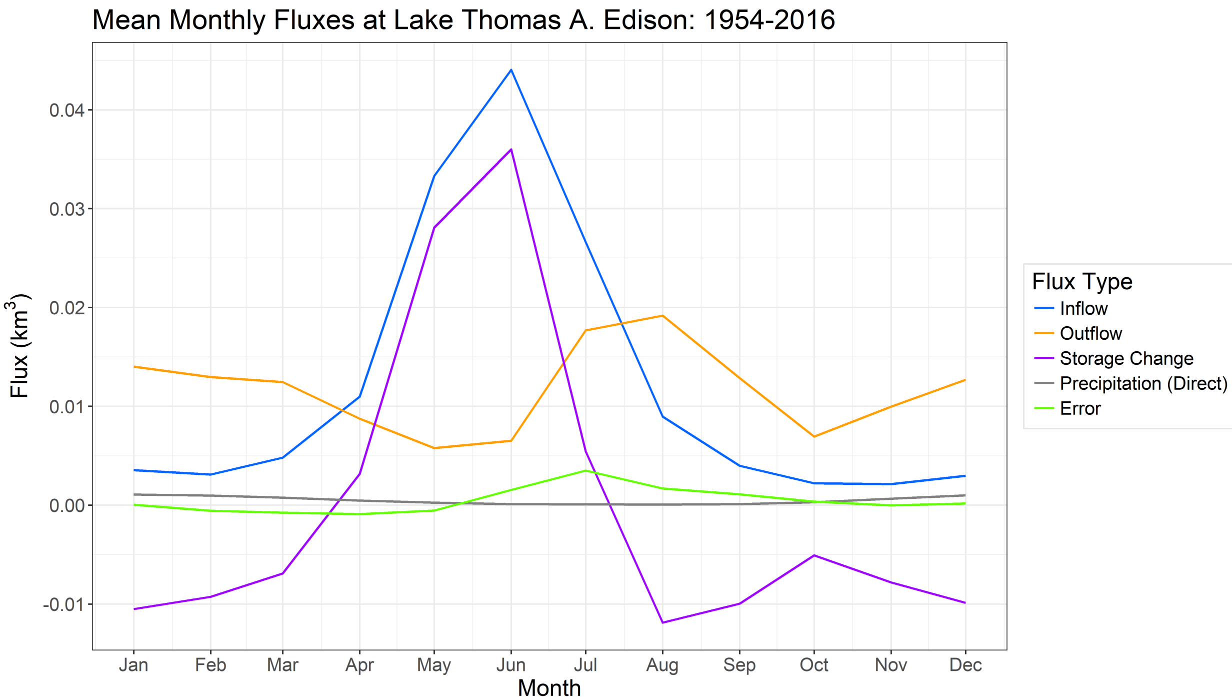

Figure 5: Monthly means of fluxes at Edison Lake over the analysis period.

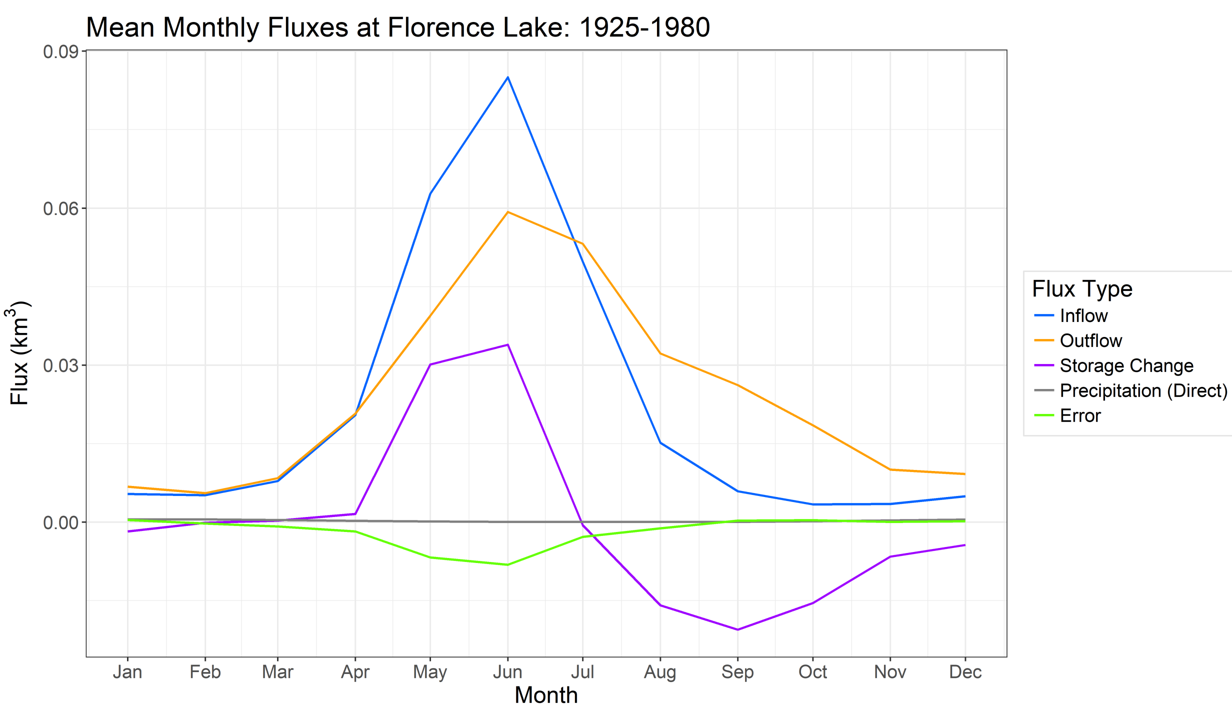

Figure 6: Monthly means of fluxes at Florence Lake over the analysis period.

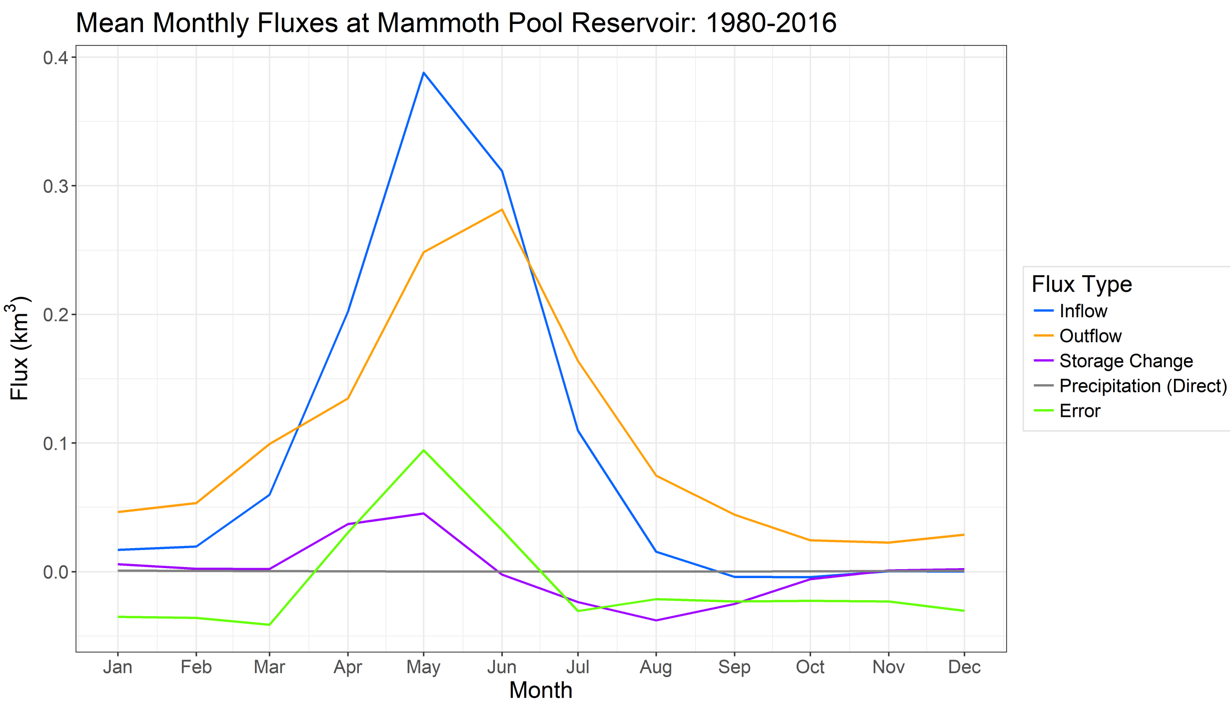

Figure 7: Monthly means of fluxes at Mammoth Pool over the analysis period.

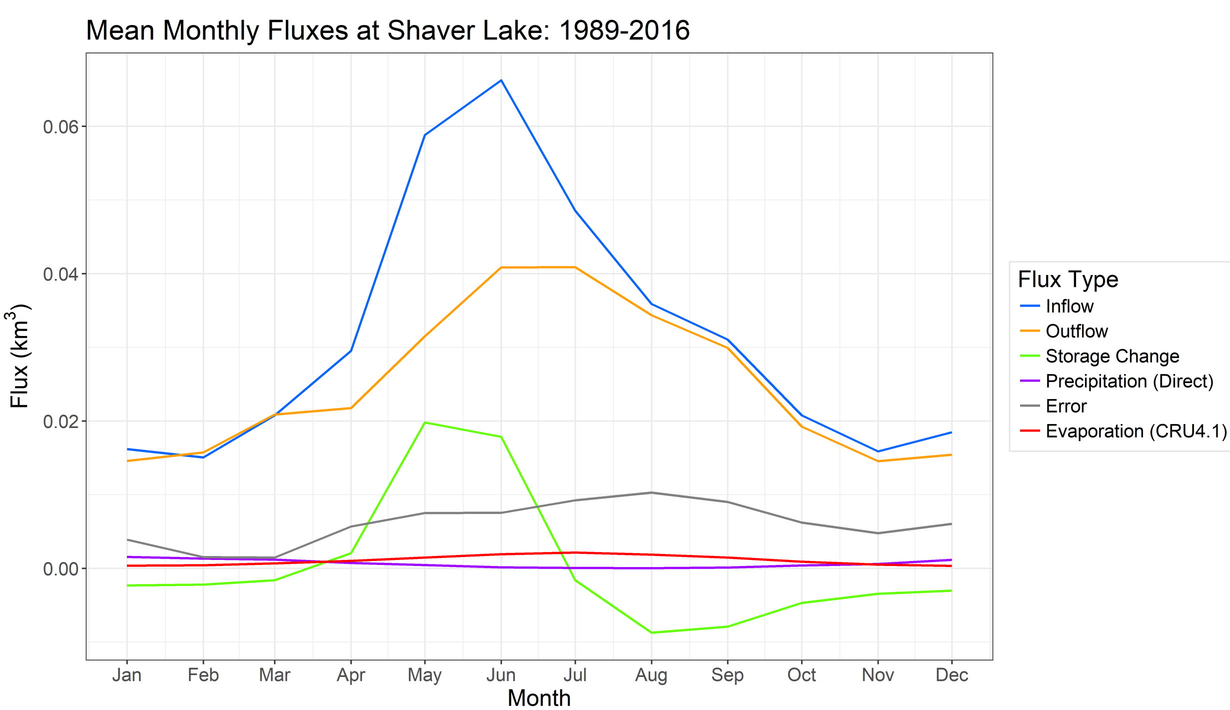

Figure 8: Monthly means of fluxes at Shaver Lake over the analysis period, with CRU potential evaporation shown in red.

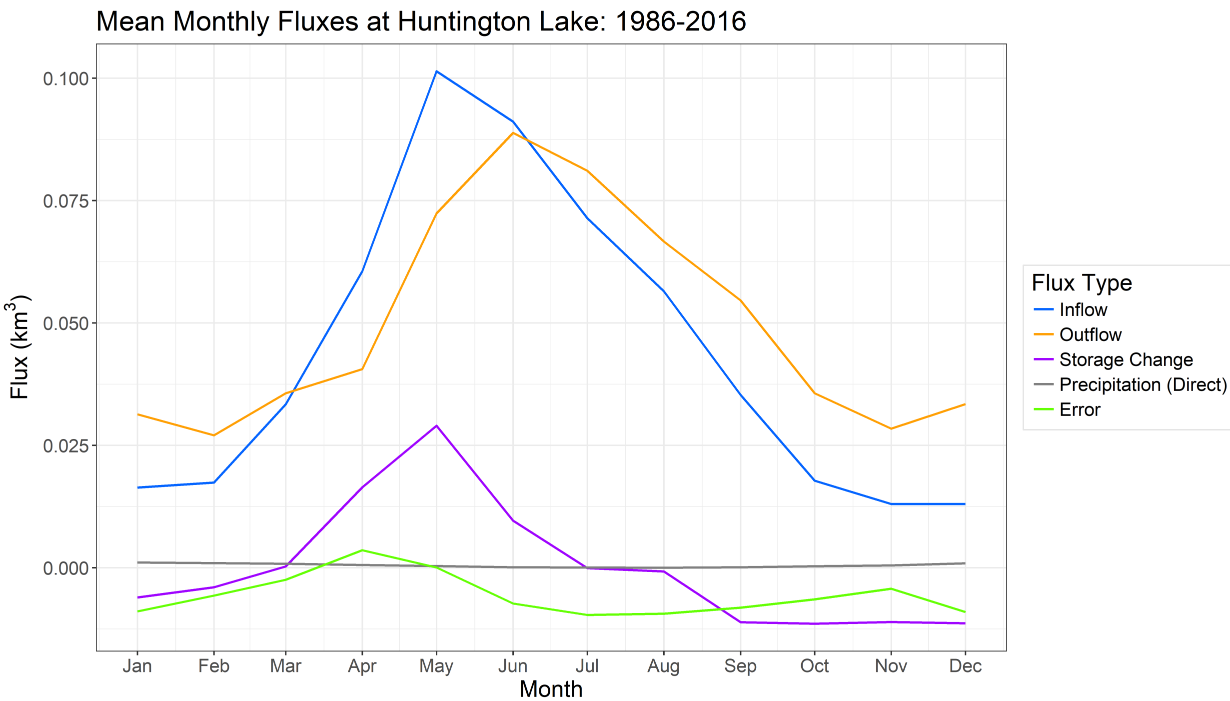

Figure 9: Monthly means of fluxes at Huntington Lake over the analysis period.

both from Huntington Lake and the Pitman Creek Diversion. Data on the Pitman Creek Diversion is available through our period of analysis, but the gages at the inlet and outlet of the conduit that measured the contribution of Huntington Lake were discontinued in the early 1980s. To overcome this, the gage at Eastwood Powerhouse was used as a proxy for inflows from Huntington. Figure 10 shows these different fluxes. Eastwood Powerhouse consistently exceeds the flow in the conduit, particularly in later months. Comparing to Figure 9, this can be seen to drive the observed negative error that would arise from either an underestimation in inflows or an overestimation of outflows.

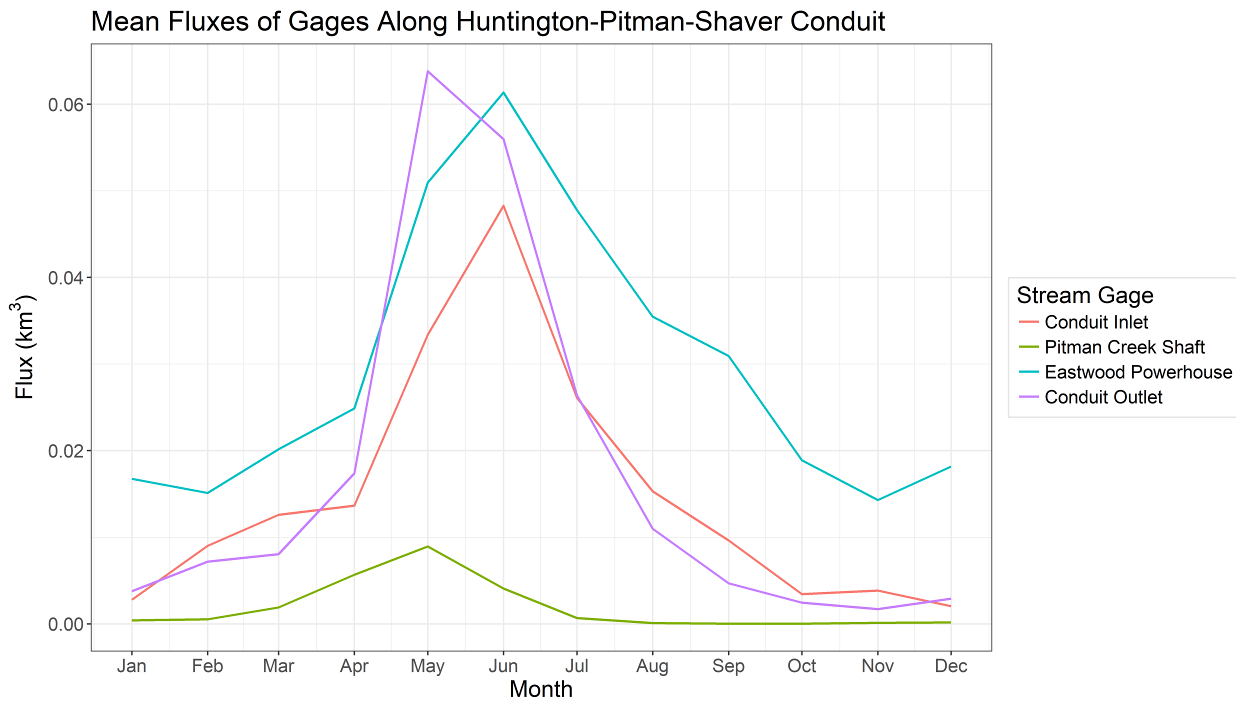

Figure 10: Fluxes along the Huntington-Pitman-Shaver conduit. Only Eastwood Powerhouse and the Pitman Creek Shaft had data for the analysis period.

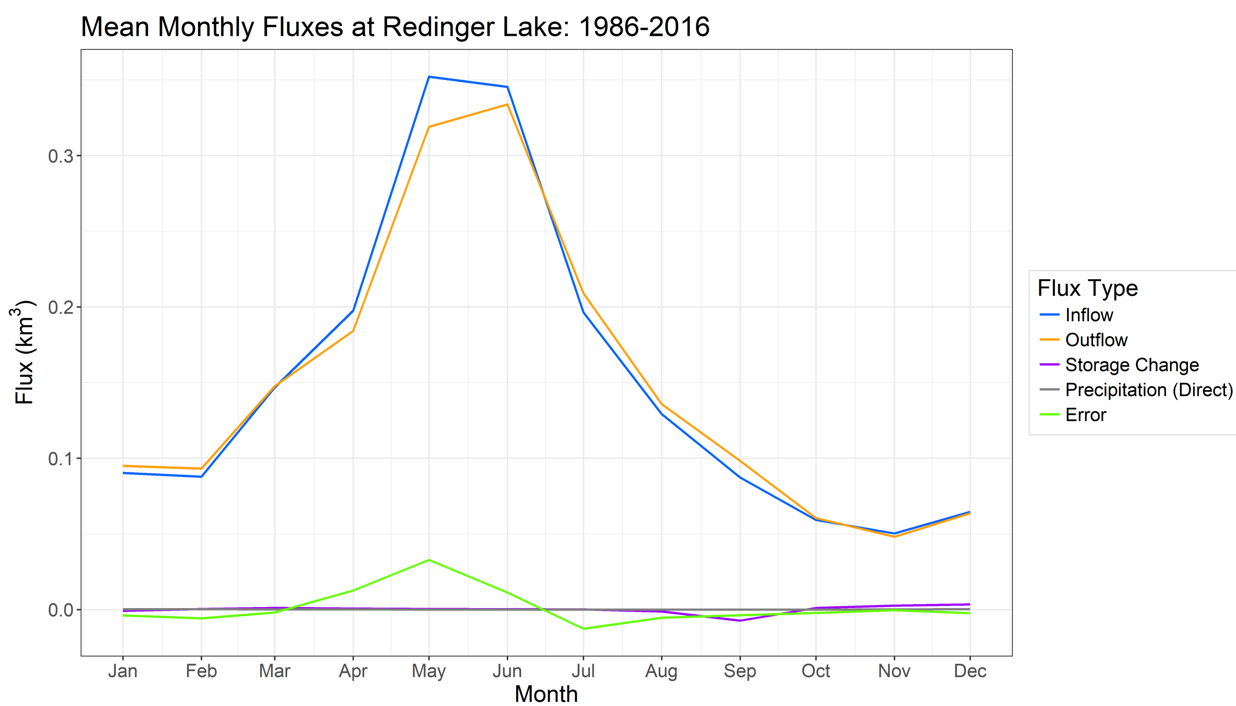

Figure 11: Monthly means of fluxes at Redinger Lake over the analysis period.

4 Conclusion

A monthly water balance was conducted for 6 reservoirs in the Big Creek System. Inflows were estimated using an area-based method, while outflows were provided by stream gages. The area-based estimation method produced reasonable seasonal curves, but consistently underestimated inflows, to the point where it was not possible to estimate evaporation or seepage using a water balance method. Diversions within the system dominate natural flows, to the extent that gaps in data (as in the case of Huntington) dominate the observed error. An investigation of CRU potential evaporation estimates suggest that evaporative losses are low compared to the fluxes in the system, although the steep changes in elevation over the grid cell limits the confidence that can be placed in these estimates.

A Additional Figures and Tables

Table 3: USGS stream and storage gages used in analysis [9, 11].

Station Name	Station Number	Period of Record	Gage Type
Florence Lake	11229600	1925/11/02 to 2016/09/30	Storage
Lake Thomas A. Edison	11231000	1954/10/12 to 2016/09/30	Storage
Mammoth Pool Reservoir	11234700	1959/10/17 to 2016/09/30	Storage
Huntington Lake	11236000	1926/10/01 to 2016/09/30	Storage
Shaver Lake	11239500	1927/01/11 to 2016/09/30	Storage
Redinger Lake	11241950	1965/10/01 to 2016/09/30	Storage
Powerhouse 3	11241800	1980/10/01 to 2016/09/30	Flow
San Joaquin River below Dam 6 (above Stev. Cr.)	11238600	1973/10/01 to 2016/09/30	Flow
Stevenson Creek below Shaver Lake	11241500	1925/06/09 to 2016/09/30	Flow
Powerhouse 4	11246530	1980/10/01 to 2016/09/30	Flow
San Joaquin River above Willow Creek	11242000	1951/03/07 to 2016/09/30	Flow
No. Fk. Stevenson Creek above Shaver Lake	11239300	1989/01/25 to 2016/09/30	Flow
Eastwood Powerhouse	11238250	1987/10/01 to 2016/09/30	Flow
Powerhouse 2A	11238400	1980/10/01 to 2016/09/30	Flow
Mammoth Pool Powerhouse	11235100	1980/10/01 to 2016/09/30	Flow
San Joaquin River above Shakeflat Creek	11234760	1959/10/01 to 2016/09/30	Flow
Portal Powerhouse	11235500	1927/10/01 to 2016/09/30	Flow
Powerhouse 1	11238100	1980/10/01 to 2016/09/30	Flow
Big Creek below Huntington Lake	11237000	1925/06/09 to 2016/09/30	Flow
South Fork San Joaquin River Near Florence Lake	11230000	1925/06/09 to 1980/09/29	Flow
Ward Tunnel at Intake at Florence Lake	11229500	1925/06/29 to 2016/09/30	Flow
Mono Creek below Lake T. A. Edison	11231500	1925/06/09 to 2016/09/30	Flow
Bear Creek near Lake Edison	11230500	1925/01/01 to 2016/09/30	Flow
Pitman Creek below Tamarack Creek	11237500	1927/12/01 to 2016/09/30	Flow
Huntington-Shaver Conduit Outlet Near Shaver Lake	11239000	1928/10/19 to 1985/07/24	Flow
Pitman Creek Shaft below Tamarack Creek near Big Creek	11237600	1986/10/01 to 2016/09/30	Flow

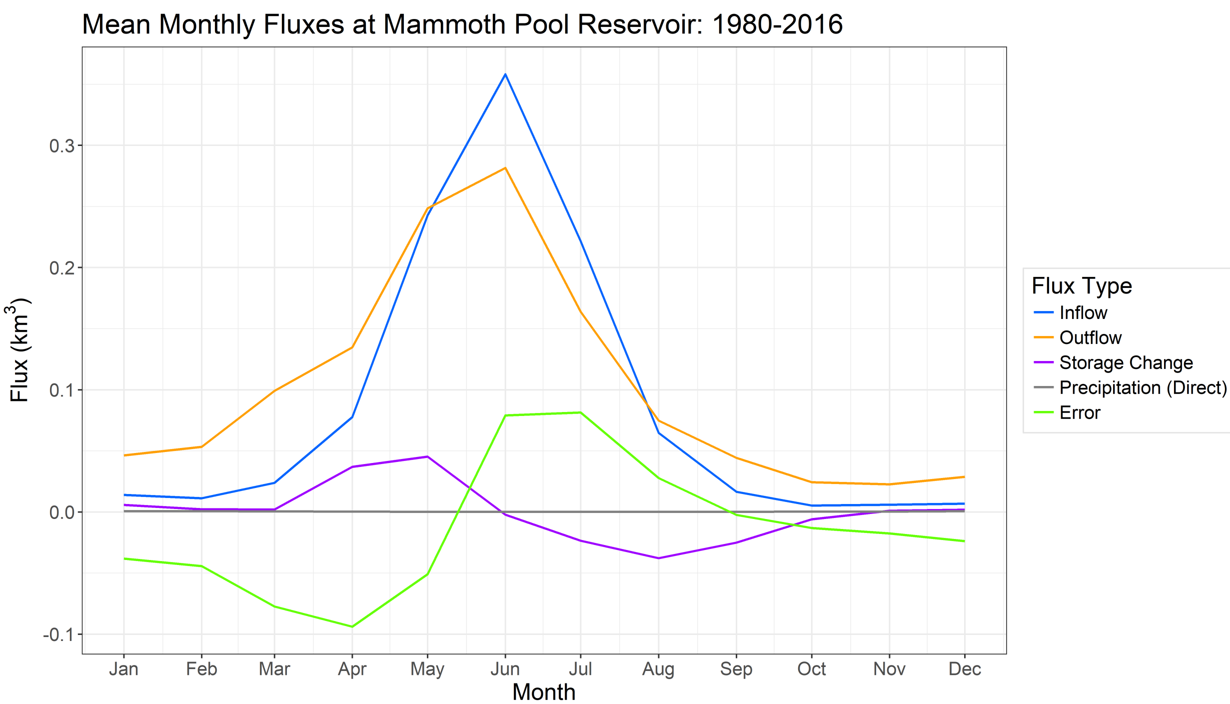

Figure 12: Yearly water balance at Mammoth Lake, using only Bear Creek as a reference watershed.

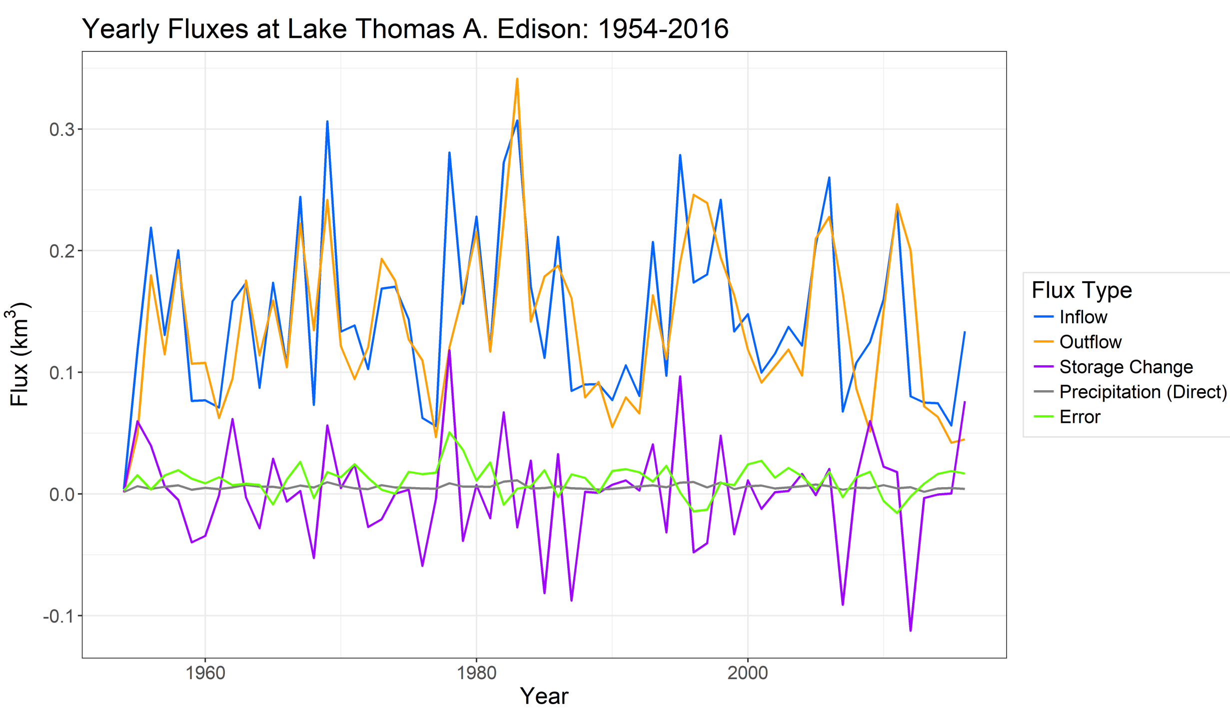

Figure 13: Yearly water balance at Edison Lake over the analysis period.

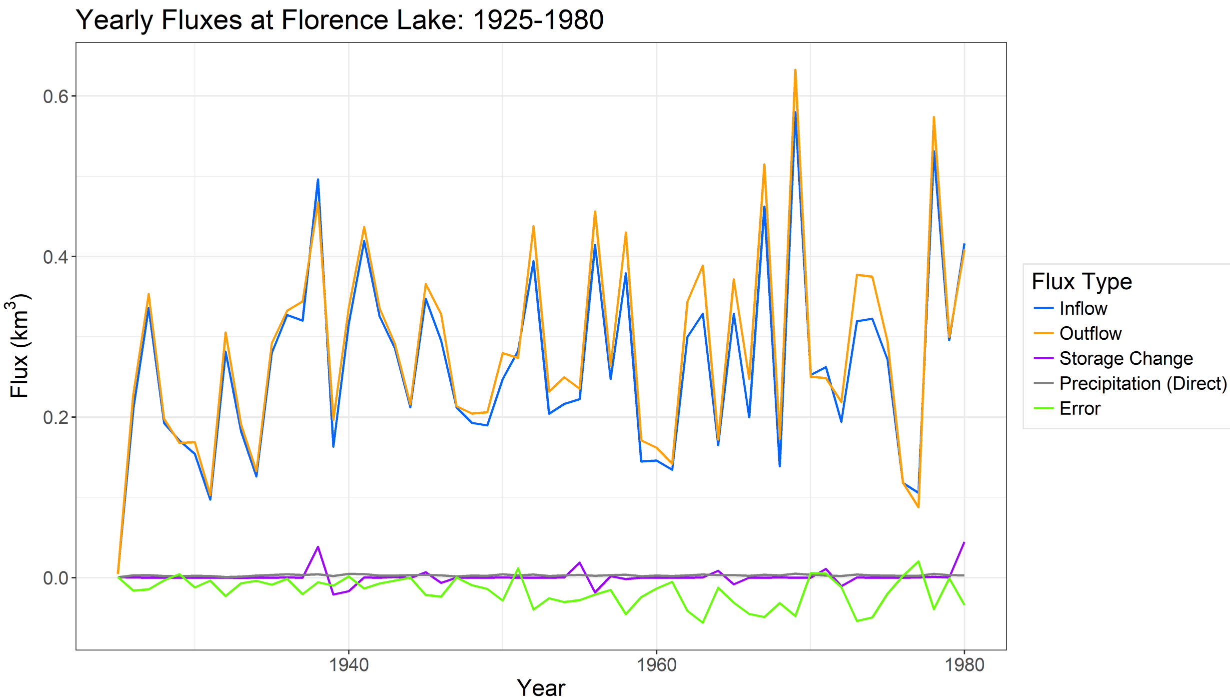

Figure 14: Yearly water balance at Florence Lake over the analysis period.

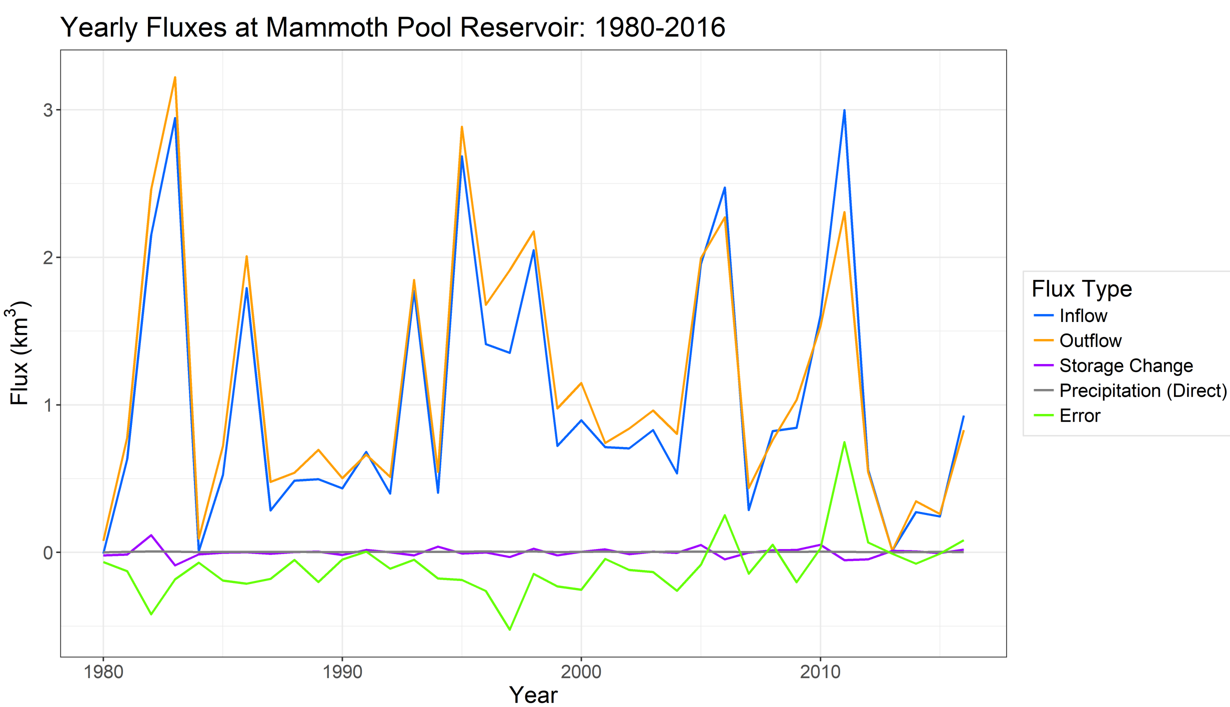

Figure 15: Yearly water balance at Mammoth Pool over the analysis period.

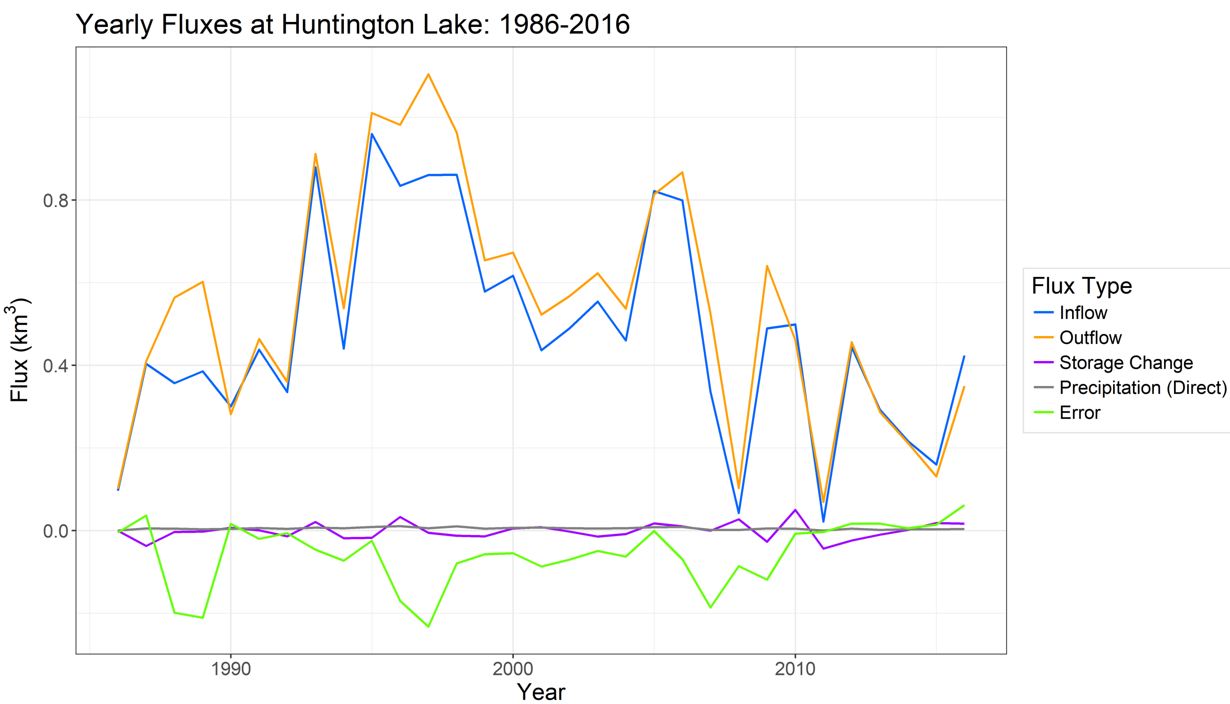

Figure 16: Yearly water balance at Huntington Lake over the analysis period.

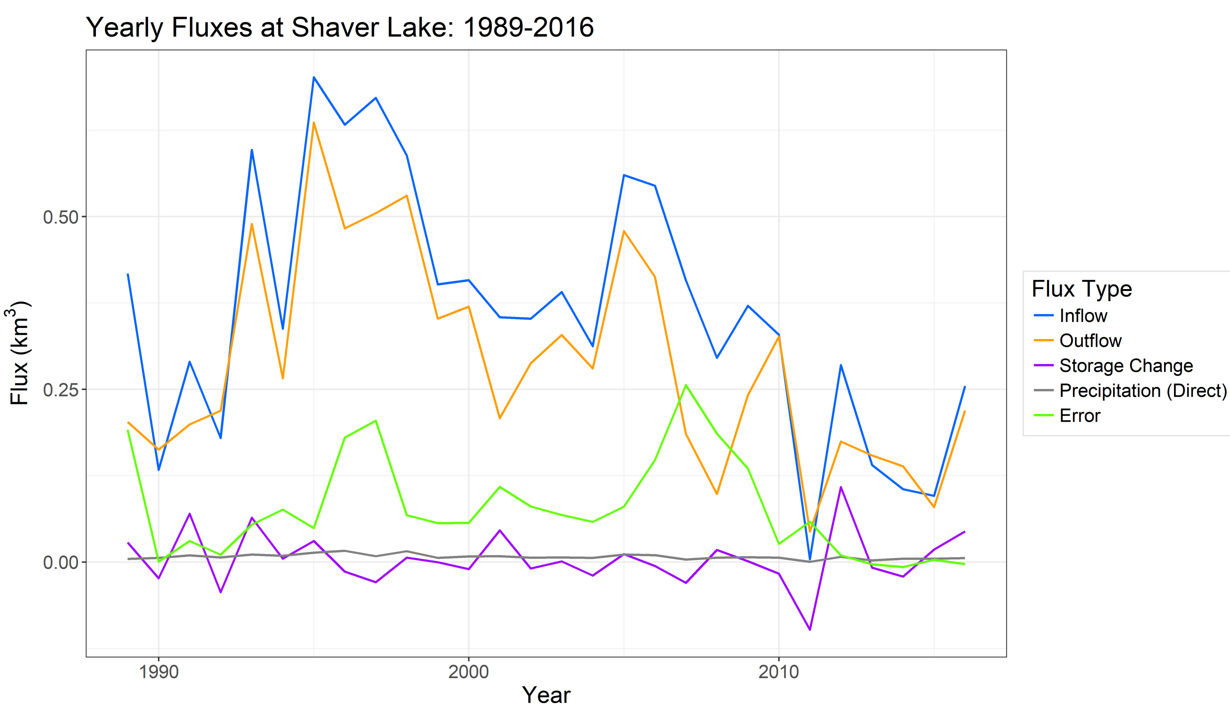

Figure 17: Yearly water balance at Shaver Lake over the analysis period.

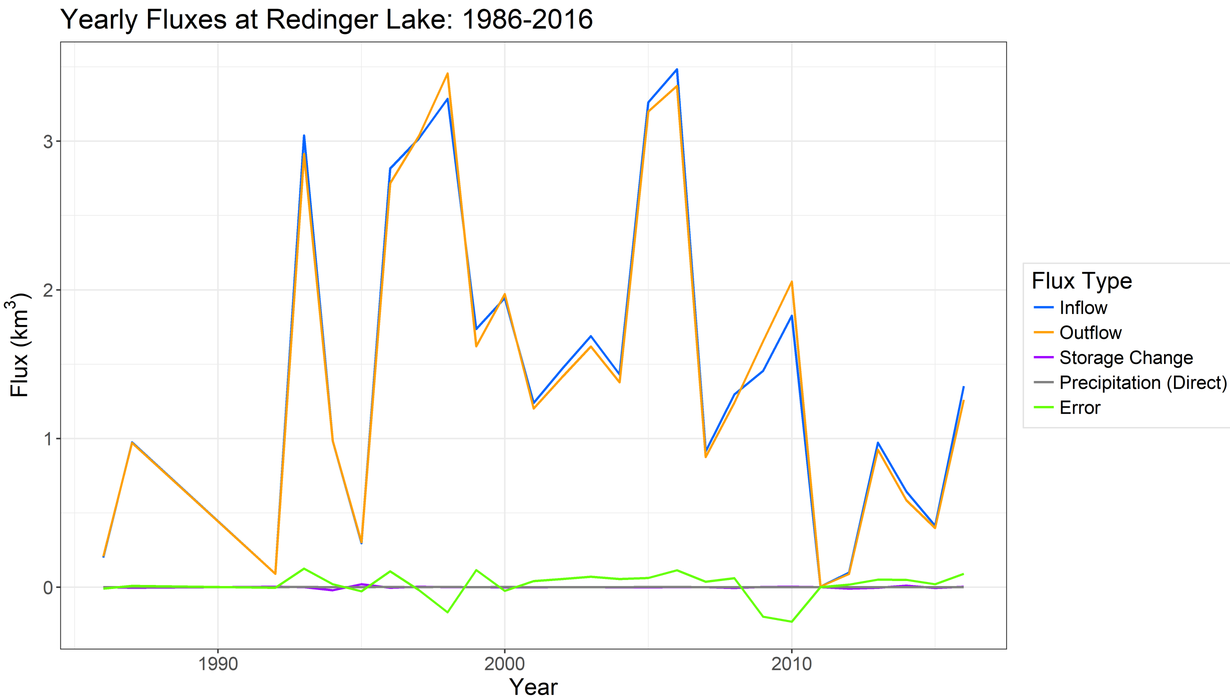

Figure 18: Yearly water balance at Redinger Lake over the analysis period.

References

[1] A. A. Solomon, D. M. Kammen, and D. Callaway, "The role of large-scale energy storage design and dispatch in the power grid: A study of very high grid penetration of variable renewable resources," *Applied Energy*, vol. 134, pp. 75–89, 2014.

[2] P. Denholm and R. Margolis, "Energy Storage Requirements for Achieving 50 % Solar Photovoltaic Energy Penetration in California," *NREL*, no. August, 2016.

[3] Combined Aquatics Working Group, "CAWG 6-Hydrology," tech. rep., Southern California Edison, 2004.

[4] M. J. Menne, I. Durre, B. Korzeniewski, S. McNeal, K. Thomas, X. Yin, S. Anthony, R. Ray, R. S. Vose, B. E. Gleason, and T. G. Houston, "Global Historical Climatology Network - Daily (GHCN-Daily), Version 3.22," 2012. [Accessed December 11, 2017].

[5] M. J. Menne, I. Durre, R. S. Vose, B. E. Gleason, and T. G. Houston, "An overview of the global historical climatology network-daily database," *Journal of Atmospheric and Oceanic Technology*, vol. 29, no. 7, pp. 897–910, 2012.

[6] University of East Anglia Climatic Research Unit, I. Harris, and P. Jones, "CRU TS4.01: Climatic Research Unit (CRU) Time-Series (TS) version 4.01 of high-resolution gridded data of month-by-month variation in climate (Jan. 1901- Dec. 2016)," 2017.

[7] I. Harris, P. Jones, T. Osborn, and D. Lister, "Updated high-resolution grids of monthly climatic observations: the cru ts3.10 dataset," *International Journal of Climatology*, vol. 34, no. 3, pp. 623–642, 2014.

[8] D. R. Maidment, *Handbook of Hydrology*.

[9] U.S. Geological Survey, “The National Map, 2017, 3DEP products and services: The National Map, 3D Elevation Program.” https://nationalmap.gov/3DEP/3dep_prodserv.html. [Web page; accessed November 2017].

[10] Southern California Edison, “Initial Information Package for the Big Creek Hydroelectric System: Alternative Liscensing Process,” Tech. Rep. May, Southern California Edison, 2000.

[11] U.S. Geological Survey, “National Water Information System data available on the World Wide Web (USGS Water Data for the Nation).” http://waterdata.usgs.gov/nwis/, 2016. [Accessed December 13, 2017].