Sediment Discharge Rates in the Sacramento River Reservoirs

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ABSTRACT

Every dam-reservoir system is subjected to the effects of eventually sedimentation from the riverbeds they sit on, These sedimentation rates can be measured by calculating the trap efficiency of a reservoir: the ratio of incoming sediment that gets trapped out of the total sediment that passes. For this study I calculated the trap efficiencies and sediment yields of three reservoir systems along the Northern Sacramento River in California: Lake Britton, Lake McCloud, and Lake Shasta. Ultimately, I wanted to see how different factors may affect trap efficiency and sedimentation throughout time; in response to the recent prolonged drought in California, I sought to record trap efficiencies from all three sites from 1975 to 2020 . To test this, I used three different types of models that used their own unique metric to calculate trap efficiency: the Brown (1944) model that uses active reservoir capacity, the Brune (1953) model that uses upstream discharge, and the Rausch and Heinemann model (1975) that uses storm detention time. The three models trap efficiencies were then used to calculate sediment yield using a model that accounts for upstream reservoir trapping. Overall results have shown that trap efficiency has remained the same range within the last forty-five years. Final calculations showed that the Brune model yielded both the consistently the highest trap efficiency (~0.9999) but the smallest yearly sediment yields. The Brown model yielded on average the lowest trap efficiency yields but also the largest range of trap efficiencies [0.5] and the largest sediment yields.

KEYWORDS

trap efficiency, sediment yield, time series, dynamic time warping, linear regression

INTRODUCTION

California is the most populated state in the United States with 39.5 million people (America Counts Staff 2021). It is also the base of many lucrative industries including agriculture and technology (Lassiter 2015). As such, water for human use might be drawn from one of California's nearly 1,500 reservoirs (Bou-Escriva et al. 2019), where water can be stored for drinking, hydroelectricity, and economic needs. Most of these reservoirs are built on naturally flowing rivers where the water is delivered throughout. In a place as big as California, it's important to maintain the reservoirs and distribute water thoroughly to the populace as most California water originates near the north but needs to be transported to the south, where there is less water. However, a growing population and current climate change, which also resulted in nearly a decade of droughts (Lassiter 2015), keeps changing how water is moved; there is great uncertainty on how California is able to access and store water supplies.

As water flows into the river, entrained materials and pollutants such as sediment can be carried to the reservoirs. Natural sediment is formed by erosion of water on the channel bed and banks due to potential energy gathered in the water by passing elevated stream paths. But because of stored energy, rivers always will hold a set amount of sediment at any time (Kondolf 1997). Because the reservoirs are blocked off to hold the water, the reservoir simultaneously holds the sediment that came with it. By design, the reservoir would eventually reach a point where it accumulates enough sediment in its storage, diminishing how well the reservoir holds water (Wisser et al. 2013). The buildup of sediment, however, is expected; reservoirs even have a section called a sediment pool dedicated to this infill (Podolak and Doyle 2015). But the main concern, specifically for reservoirs in California, is the lifetime and how long the reservoir can last. In the US, the numbers and volumes of reservoir storage surveys have significantly decreased since the 2000s, leaving out for future management of reservoirs (Podolak and Doyle 2015).

Trap efficiency is a metric to quantify sedimentation deposition rates in a reservoir; it is calculated as the ratio of incoming sediment trapped by the reservoir to the total sediment inflow (Rausch and Heinemann 1975). An increased ratio of sediment to inflow also decreases the lifetime of the reservoir as more sediment would come in with the inflow (Wisser et al 2013). High trap efficiency is linked to structural damage on the dam and any turbines installed that produce hydroelectricity (Minear and Kondolf 2009), backwater flooding with sediment buildup blocking downstream flow (Fan and Morris 1992), and further downstream erosion with sediment removal of water by the dams, because the water needs a way to dissipate surplus potential energy (Kondolf 1997). High trap efficiency also can harm biotic organisms. Build up of sediment causes the waters to be more turbulent, harming fish populations (Rausch and Heinemann 1975, Kjelland et al. 2015). Backup of sediment also builds up nutrients in the water, leading to eutrophication in the reservoir and decreasing water quality (Rausch and Heinemann 1975). Unfortunately because of the multitude of factors, trap efficiency and reservoir lifetimes are difficult to accurately calculate.

Models are the primary way of calculating sedimentation rates, using different variables to calculate the values. However, local factors in reservoir sites make it difficult to develop one model to satisfy all; thus many different sedimentation, trap efficiency and reservoir lifetime models have been developed to fit their studied regions. Some models take into account the sediment size and weight in the river, noting the basis for how easily sediment moves through the water and ultimately sediment yield (Garg and Jothiprakash 2008, Kondolf et al. 2014). The weather climate in an area can be prone to storms which contributes more inflow in rivers and changes the runoff detention time, a measure of how long sediment stays in the reservoir, and the particle settling velocity (Rausch and Heinemann 1975). Sometimes, multiple reservoirs can be built on the same river system in which sediment trapping in dams upstream affects the dams downstream (Minear and Kondolf 2009). These models, however, tend to use only one of the primary metric or explanatory variables, making the assumption that only one factor is responsible for trap efficiency calculations when in reality many factors are in play when calculating an accurate value. Because of this constraint, some of these developed models may easily over or under predict trap efficiency (Rausch and Heinemann 1975). Therefore, identifying which of these variables has the most predictive power requires examining the trap efficiency models, and eventually reservoir lifetimes, together.

In this study, I ask how different factors unique in river basins, sediments, and storm patterns affect sediment deposition, and ultimately reservoir capacity loss rate in Lake Britton, Lake McCloud, and Lake Shasta, three reservoirs along the northern Sacramento River. To quantify sediment deposition and loss rate, I will evaluate trap efficiency as a ratio and reservoir lifetime as an estimated number of years, with different models. There are three areas in using these models that I investigated: (1) how do the metrics in each model estimate trap efficiency over time, (2) how do their estimates differ between each site, and most importantly, (3) which factors influence trap efficiency and reservoir lifetime estimates the most.

METHODS

Study site

The Sacramento River is the largest river in California with its total watershed area of 69,000 km^2 providing 31 percent of the state's surface water runoff. The main tributary stretches for 560 km from the Klamath mountains to where it meets the San Joaquin river at the Delta Front providing the denizens with drinking and irrigation water (Lassiter 2015). Additional incoming tributaries contribute a significant proportion of the Sacramento River's watershed and runoff. The two major, northern-most tributaries are the Pit (333 km) and McCloud (124 km) rivers that feed into the main tributary near Redding, California where it meets into one of the largest reservoirs in the state (and in the country), and and continue on the main tract towards the delta.

The Sacrmaento river, in particular, has an interesting history and environmental situation regarding its sediment load. In the mid 1850s, hydraulic mining during the Gold Rush, was prevalent in the Sacramento River, which produced more sediment than from natural weathering processes. Before the Gold Rush, sediment load was 0.8 million metric tons per year; Sediment yield at the peak of hydraulic mining (1860s) was 7.3 million metric tons per year (Domagalski 2001). Some of those effects are still felt today. Old debris from the Gold Rush is still present. Some of the sediment cores, containing up to 43% of hydraulic mining debris, can still be found downstream from the river in the San Francisco Bay (Bouse et al 2015). With better knowledge of the main factors of sedimentation, it may be possible to minimize trap efficiency and prolong reservoir lifetime.

In this study, I looked at three different dam/reservoir systems on the northern Sacramento river network.

With the need for water storage, dams can be found at every presage of each river tributary. The two most upstream reservoirs from the Pit and McCloud river feed into the larger reservoir downstream. From upstream to downstream: (Figure 1)

Lake Britton (41.0221, -121.6767): This reservoir is impounded by the Pit 3 Dam. The Pit 3 Dam was completed in 1925. The odd name of the dam originates from its owner, PG&E as the company owns multiple dams across the Pit river. As such, the dam-reservoir primarily generates hydroelectric power. The Pit 3 dam is a concrete gravity dam with a total reservoir storage capacity of 51,655,000 m^3.

Lake McCloud (41.1349, -122.0750): This reservoir is impounded by the McCloud Dam. The McCloud Dam was completed in 1965. This dam-reservoir is also owned by PG&E and generates hydroelectric power. There is a notable salmon and brown trout population that lives here, due to the lake's annual cold temperatures. The McCloud dam is a rock-fill dam with a total reservoir storage capacity of 43,400,000 m^3.

Lake Shasta (40.7186, -122.4193): This reservoir is impounded by the Shasta Dam. The Shasta Dam was completed in 1949. Lake Shasta is the largest reservoir in the state, playing a major role in the California Central Valley Project managed by the US Bureau of Reclamation. In addition to generating hydroelectric power and storing water, the reservoir has a special role in separating saline water from fresh water; by maintaining constant freshwater flows, the freshwater is able to prevent saltwater creep downstream. Large populations of salmon are present in this area. The Shasta dam is a concrete gravity dam with a total reservoir storage capacity of 5,614,800,960 m^3.

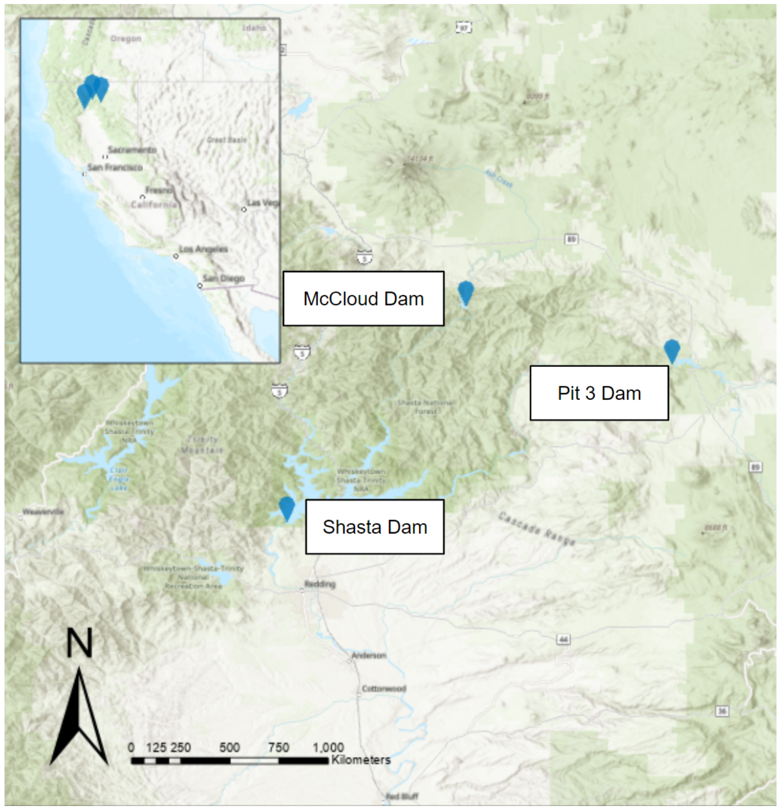

Figure 1. Three dams located on the Sacramento River. From most upstream to downstream 1) Pit 3 Dam, 2) McCloud Dam, 3) Shasta Dam

Trap efficiency models

Brown 1944

Brown (1944) developed a general trap efficiency model for reservoirs. In this model, he used the entire constant drainage area of the reservoir (as the input of the amount of water) to the active reservoir capacity at a time.

Trap efficiency for Brown (1944) is calculated as:

$$TE = 1 - \frac{1}{(1+(0.00021 \times K_{t-1}/W))}$$

where *TE* is the trap efficiency of a reservoir (decimal percent), K_{t-1} is the active reservoir capacity of a reservoir at time t-1 (m^3), and *W* is the drainage area or the reservoir (km^2).

In his research, Brown plotted the association between capacity-watershed and trap efficiencies (Figure 2). This was known as the Brown curve.

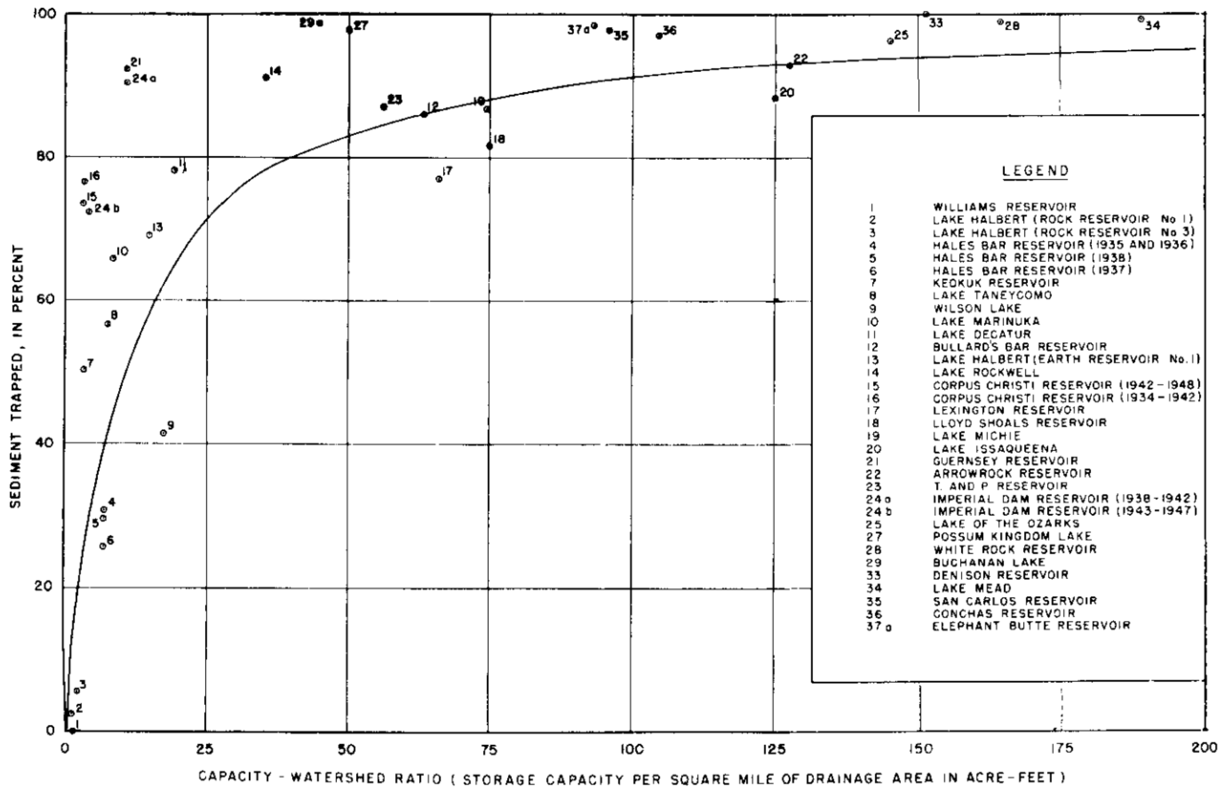

Figure 2. Original Brown 1944 curves. Relates active capacity ratio to drainage area (Brune 1953).

Brune 1953

Most modern trap efficiency models are based on the findings from Brune (1953). In his study, Brune establishes that the capacity inflow ratio offers closer correlation to reservoir trap efficiency. Older 1950 models, like Brown (1944), failed to account for watershed runoff and relative (seasonal) capacity (Brune 1953). Brune tested this model on forty different reservoirs of varying sizes and regions throughout the US, possibly leading to its common use of the model throughout today's world.

Trap efficiency for Brune (1953) is calculated as:

$$TE = 1 - \frac{0.05}{\sqrt{CI}},\ CI = \frac{K}{Q},$$

where *TE* is the trap efficiency of a reservoir (decimal percent), *CI* is the capacity-inflow ratio, calculated by the ratio of the total reservoir storage *K* (km^3) and the mean annual discharge at the reservoir site *Q* (km^3).

Brune was able to form a Brune curve, where he plotted the association between capacity-inflow ratio and trap efficiencies at different sites (Figure 3); the Brune curve is still commonly used by other studies today.

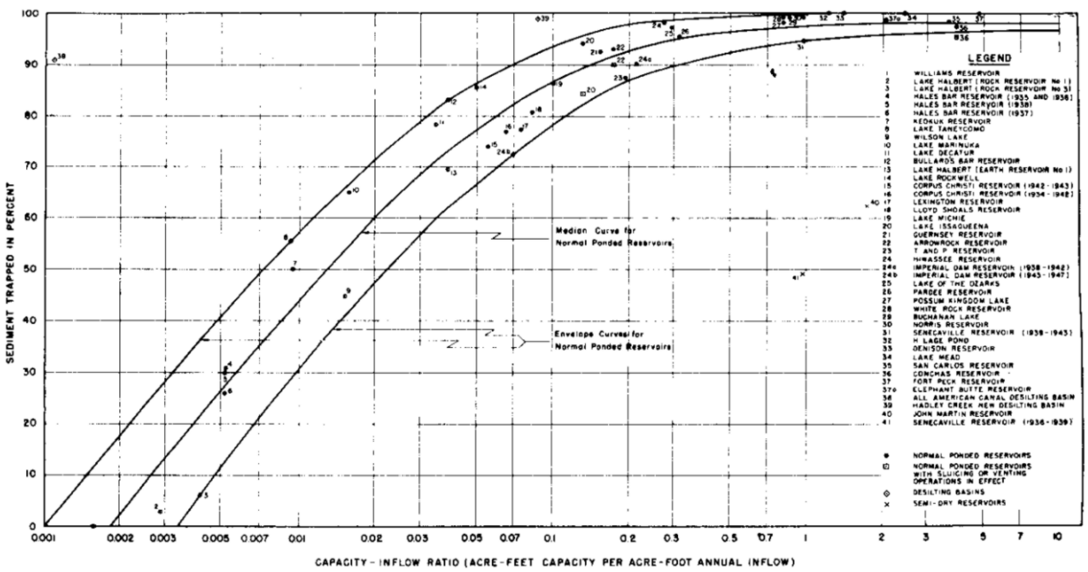

Figure 3. Original Brune 1953 curves. Relates total reservoir capacity to inflow discharge (Brune 1953).

Rausch & Heinemann 1975

As the C/I ratio used in Brune (1953) takes into account runoff, Rausch and Heinemann (1975) looked at trap efficiency based on storm and season which causes variability in runoff and sediment yield. Their different methodology resulted from the Brune model's tendency to overestimate trap efficiency in most instances. To accomplish storm variability, Rausch and Heinemann based their model on the detention time (how long water stays in the reservoir) between inflow and outflow discharge. This model was developed for three reservoirs in Central Missouri where rain events are moderately common, averaging 41 inches of rain per year (Dailey 2009); this model might work well with climate conditions of Northern California averaging 33.5 inches of rain per year (Current Results 2020).

Trap efficiency for Rausch and Heinemann (1975) is calculated as:

$$TE = 100/e^{\alpha e^{\beta_1 T_D + \beta_2 ln(Q_p)}}$$

where *TE* is the trap efficiency of a reservoir (decimal percent), α/β are regression coefficients that take into account other characteristics of the reservoir (the reservoir capacity below the lowest spillway intake, length of reservoir, and depth), Q_p is the maximum mean inflow at a day during the storm event, and T_D is the stormwater detention time (days).

Stormwater detention time can be calculated by plotting both inflow and outflow discharges of the reservoir on a hydrograph (time vs. discharge) (Figure 4). In this model, there are two ways that detention time is calculated. One ($T_{D,1}$) where the increment of inflow from a previous storm was not discharged until a succeeding storm. The other ($T_{D,2}$) where both an increment of inflow entered and was discharged during the same storm period.

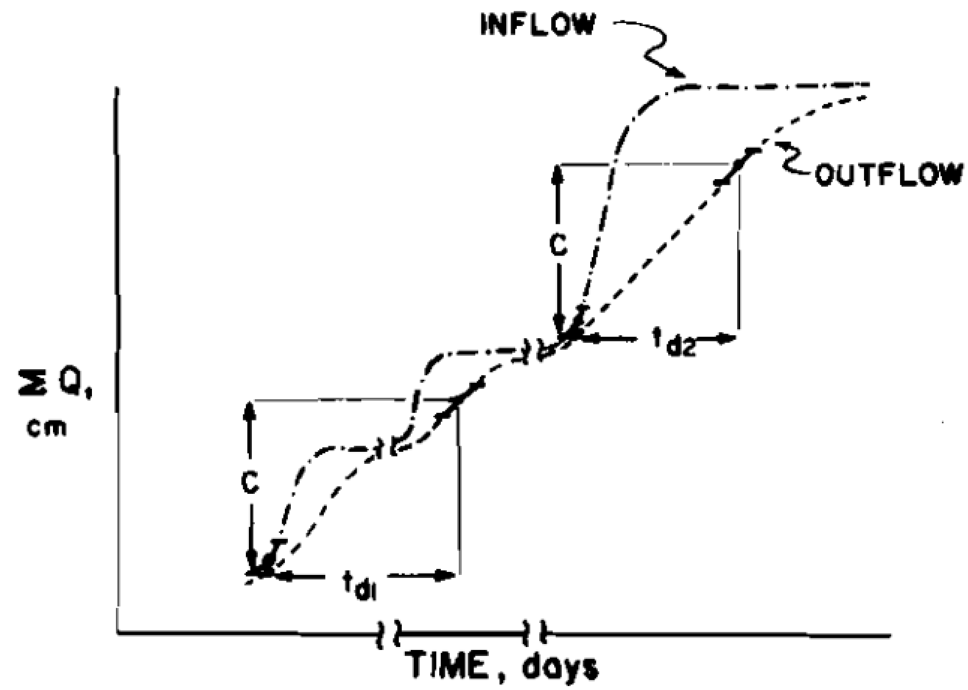

Figure 4. The hydrograph used in study to find stormwater detention time (Rausch and Heinemann 1975).

Each model requires different data to calculate trap efficiency (Table 1). The first three variables (active reservoir storage, inflow discharge, and outflow discharge) are all dynamic values that can change through time, while the other two (drainage area, total reservoir storage) are constant values.

Table 1. Variables used between each trap efficiency model. Active reservoir storage, inflow discharge, and outflow discharge are dynamic variables subjected to change throughout time. Drainage area and total reservoir storage, at least assumed for this study, are constant and do not change over time.

	Metric	Brown (1944)	Brune (1953)	Rausch & Heinemann (1975)
Dynamic variables	Active Reservoir Storage (volume)	✔		
	Inflow Discharge (volume per time)		✔	✔
	Outflow Discharge (volume per time)			✔
Constant variables	Drainage Area (area)	✔		
	Total Reservoir Storage (volume)		✔	

Sedimentation models

Minear & Kondolf 2009

The trap efficiency values can then be entered into sedimentation models, where the amount of sediment and sediment yield for the reservoir could actually be calculated. A drawback for prior models was their inability to take into account overarching temporal or spatial sedimentation patterns. For example, an upstream dam can trap a number of sediment above. This may subject the downstream waters to different rates of erosion which can then affect the next dam the river reaches. In response, Minear and Kondolf (2009) developed a spreadsheet-based model, the three-worksheet (3W) model, focusing on the effects that upstream reservoirs have on sedimentation/trap efficiency.

The original Minear and Kondolf (2009) model was developed to look at reservoirs in California where many of the reservoirs are on the same river. This model was also used in Asian

Mekong River Basin (Kondolf et al. 2014) where the region has diverse geological characteristics.

By using these models, the actual sedimentation volume of a reservoir R can be calculated, which is essential for calculating loss rates and ultimately reservoir lifetime. Trap efficiency from any of the three previous models can be used in conjunction with these sets of models:

$$R_{a,t} = \{TE_{a,t-1}[A_aY - (R_b + R_c + \ldots)]\}$$

$$R_{b,t} = \{TE_{b,t-1}[A_bY - (R_c)]\}$$

$$R_{c,t} = \{TE_{c,t-1}[A_bY]\}$$

where R is the volume of sediment trapped (m^3), subscripts *a,b,c* represent different reservoirs with *a* from most downstream *c* to most upstream, *TE* is trap efficiency at time t-1 (decimal percent), and Y is sediment yield (m^3km^2 per time step).

Data collection

This study analyzed secondary data from online sources using a variety of different models. I used online datasets for the Pit 3, McCloud, and Shasta dams available on the WaterData Database hosted by the United States Geological Survey (USGS 2021). Other information needed, including watershed area, were found from other sources such as the US Bureau of Reclamation website (USBR 2021).

The USGS records water data through a select number of gauges at different sites along a river. For each site, the coordinates and drainage area at the site are given in the description. However, further metrics were split up into different site types matching with the location the gauge is in. I used two different site types for this study. The first site types were “Stream Sites” where annual, monthly, and daily discharge are recorded by the USGS gages; these are found along stream channels. The second site types were “Lake Sites” where active reservoir storage is recorded; these, in relation to rivers, are found at the mouth of the reservoir lake.

I required data from three gauges to have sufficient information for each dam-reservoir: one Stream Site upstream from the reservoir, one Lake site at the reservoir, and one Stream Site downstream from the reservoir resulting in, at minimum, nine different sites total needed. Unfortunately, some Lake sites where multiple tributaries fed/discharge into had a limited number of stations that recorded inflow/outflow. To accommodate for missing data, I scaled inflow/outflow volumes noting the drainage area of the individual gage station and the drainage area of the entire reservoir.

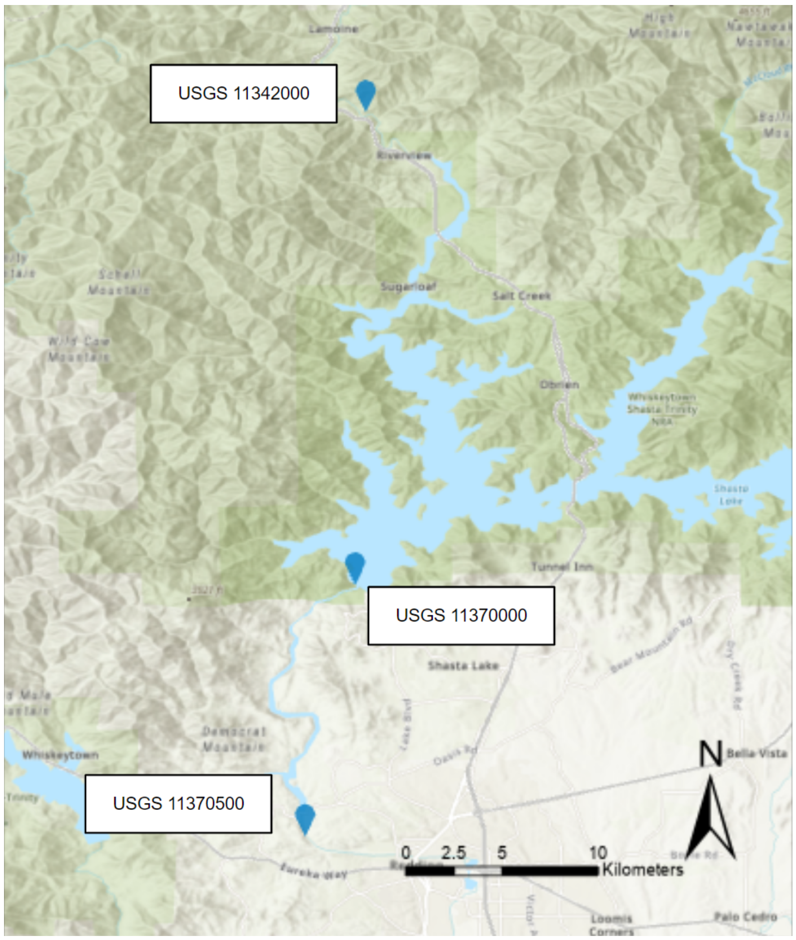

Figure 5. Three USGS gage stations near Lake Shasta reservoir. The northmost being the upstream Stream Site, the middle being the Lake Site, and southernmost being the downstream Stream Site.

The earliest data for flow and capacity ratings between all three sites (six stream sites, three lake sites) start from January 1, 1975, meaning any time series analysis would have to start from 1975. The end date for the time series, in conjunction with this time of study, was set on December 31, 2020.

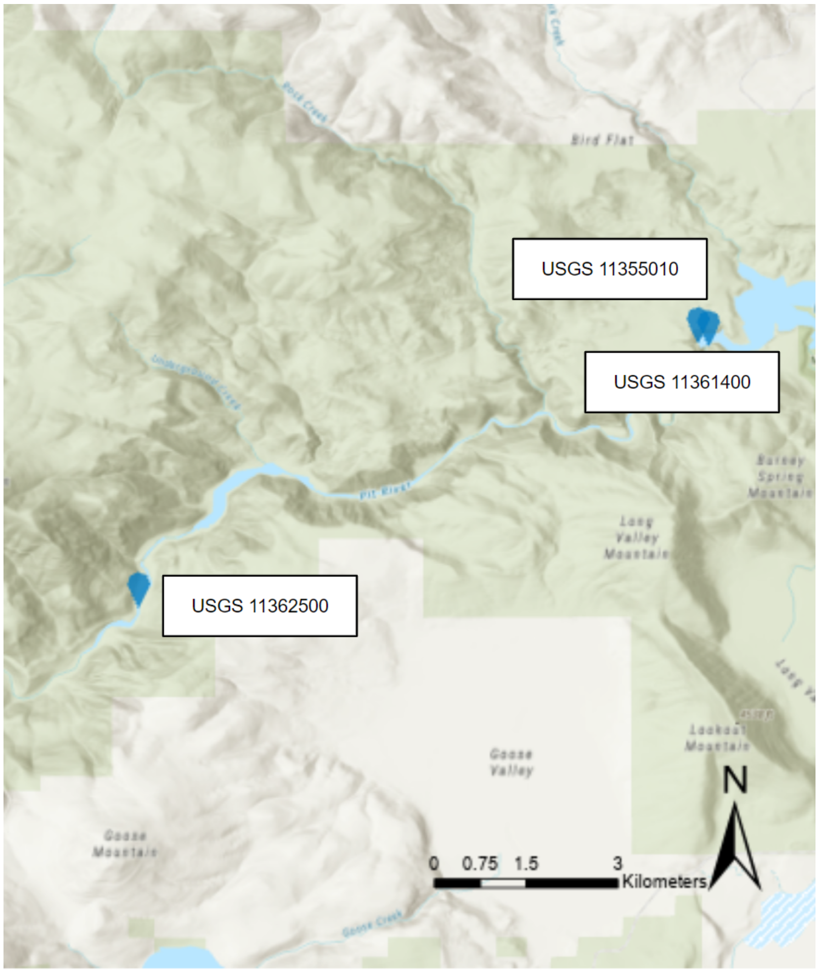

Figure 6. Three USGS gage stations near Lake Britton reservoir.

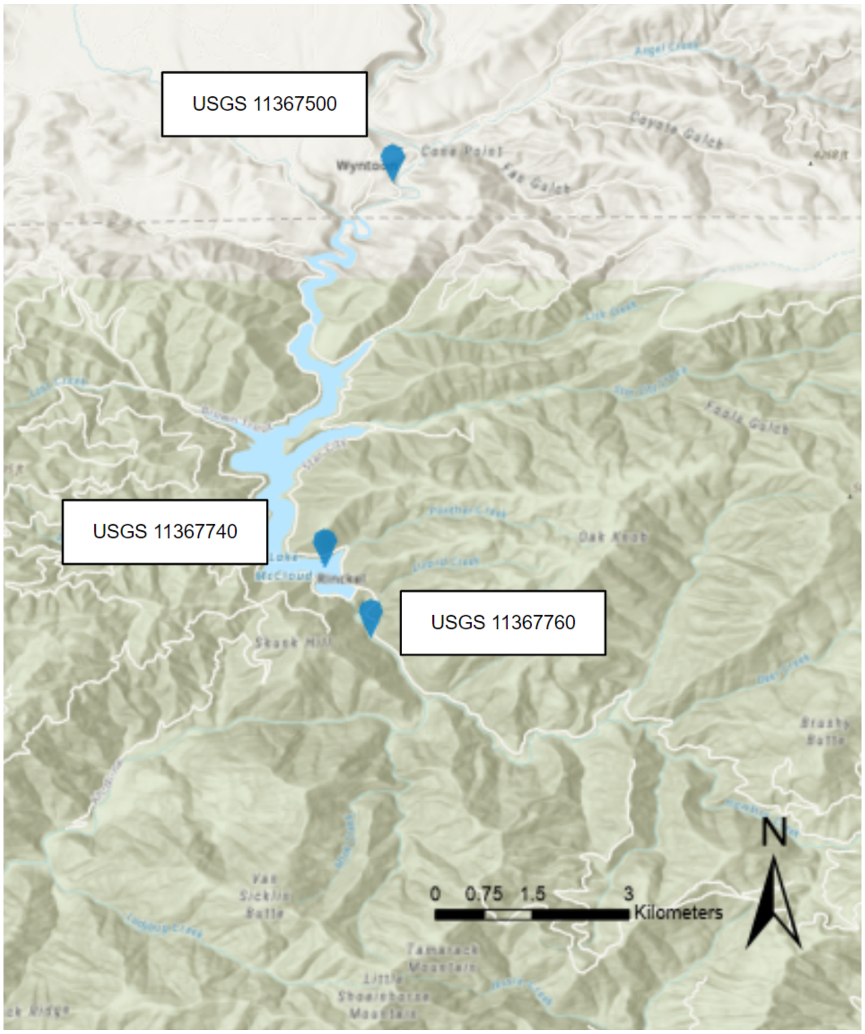

Figure 7. Three USGS gage stations near Lake McCloud reservoir.

Data analysis

Following the goals of the project, I analyzed the data using both in MS Excel 2010 and using RStudio Version 1.3.1093 (StataCorp 2021) to look at trap efficiency and reservoir lifetime values. The first analysis examined trends in trap efficiencies from 1975 to 2020 using a time series for each individual model and site, paying specific attention to the differences between the models; I will also be comparing the sediment yield values made from each model. In the second analysis, I compared the trap efficiency and sedimentation yield values, trends, and averages, regarding the site itself. The last analysis was to see how each factor in each variable used in their respective trap efficiency model actually fits with the data generated.

Time series analysis

I ran a simple time series analysis on all combinations of models and sites from 1973. After generating all time series, I first looked for any trends, variations, or fluctuations in both trap efficiency values and rate of change (Gill 1979). I made sure to note any common years where trap efficiency values between different models or sites looked similar or not. I also aligned the trap efficiency time series with the corresponding sedimentation yield time series to directly see how both were related.

I also used another way, called Dynamic Time Warping, to find significant differences in trends.In a Dynamic Time warping algorithm, two time series are compared to one another by calculating the distance between points. Those distance values are calculated between time series with similar trends rather than those aligned on the same date (Berndt & Clifford, 1944). The algorithm was imported as the “TSdist" library, into R (Giorgino 2009) .

Linear regression Analysis

To find the association between two different variables, I also used a simple linear regression model to find association between different factors and trap efficiency, and ultimately see how well the model/equation can predict other values.. In order to find an association between these outside factors and trap efficiency, the unique metric of each model (active reservoir capacity, capacity/inflow, detention time) served as the independent predictor variables while the dependent variable was the trap efficiency value itself. From there, a general trending equation was calculated to make a line of best fit.

RESULTS

Individual analysis model data: how do different models estimate trap efficiency over time?

I used three different models utilizing different metrics in active reservoir storage, upstream discharge, and storm event detention time to calculate trap efficiencies in Lake Britton, Lake McCloud, and Lake Shasta. From the results, each trap efficiency model exhibits a different range of values for trap efficiency and subsequently sediment yield.

Lake Britton

In the Lake Britton site, the Brown model generated the lowest trap efficiency values (Figure 8), the Rausch & Heinemann models generated moderate trap efficiency values (Table 2), and the Brune model generated the highest trap efficiency values out of all three models (Figure 9). Those trap efficiency values were then used in conjunction with the 3W model to calculate sedimentation yield. The lowest sediment yield values came from the Brune trap efficiency values while the largest sediment yield values came from the Brown trap efficiency.

There is a very clear, distinct relationship between the time series pattern of the Brown model and the sediment yield calculation in that as demonstrated by a similar shape pattern mirroring the two (Figure 8). This pattern could be traced back to the way the 3W model is set up, needing to know the sediment volume trapped which is calculated through the difference of the total reservoir storage and the active reservoir storage for that time step, the same main independent variable used in the Brown model. This mirrored negative relationship suggests that when the trap efficiency decreases, the sediment yield increases, and when the trap efficiency increases, the sediment yield decreases.

The Brune model, using inflow as the main metric, however, exhibits a different relationship between trap efficiency and sediment yield. The trap efficiency time series pattern, comparatively from the Brown model, is more varied and dissimilar from the sediment yield time series shape calculated (Figure 9). But although the trap efficiency time series shape may not show any obvious pattern or relationship, the Brune model values somewhat match the dips, peaks, and trends from sediment yield, suggesting a more proportional positive relationship: when trap efficiency increases, sediment yield will increase, and when trap efficiency decreases, sediment yield will decrease. For example the sudden decrease in trap efficiency to its relative minimum value around 1983 is also exhibited in the sediment yield at the same year. The peak in trap efficiency around 1987 is also marked by increased sediment yield that same year. The range of trap efficiency values themselves is more narrow (0.99993-0.99996) (Figure 2) than the values from the Brown model (0.41-0.45) (Figure 8). But looking closer at both trap efficiency models, the Brown model seems to have shown an outlier at the beginning of the time series from about 1975-1977, where the trap efficiency was around 0.2. After 1977 though, most trap efficiency values were around (0.41 - 0.45). The Brune model, however, did not record this outlier instance in its time series.

As the Rausch & Heinemann model tracks trap efficiency during periodic storm events, a continuous time series could not be made, but the relationship between trap efficiency and sediment yield can still be observed. For most cases, there was an association between increased detention time and increased maximum inflow discharge, both factoring to increased trap efficiency values; the January - February 1997 and February 2017 storm events both had detention times of 8 days, but since the 2017 event had a larger maximum inflow, the trap efficiency for the 2017 was bigger than the 1997 event (Table 2). Overall, lower trap efficiency values generated higher sediment yield values. The February - March 1986 occurrence might be an outlier to this association, as although it has the largest trap efficiency (0.784) out of all entries, it produced the highest sediment yield of 126.7335 $m^3/km^2/yr$. The second largest sediment yield 112.895 $m^3/km^2/yr$ was in January 1980 which had the smallest trap efficiency out of all entries (0.700).

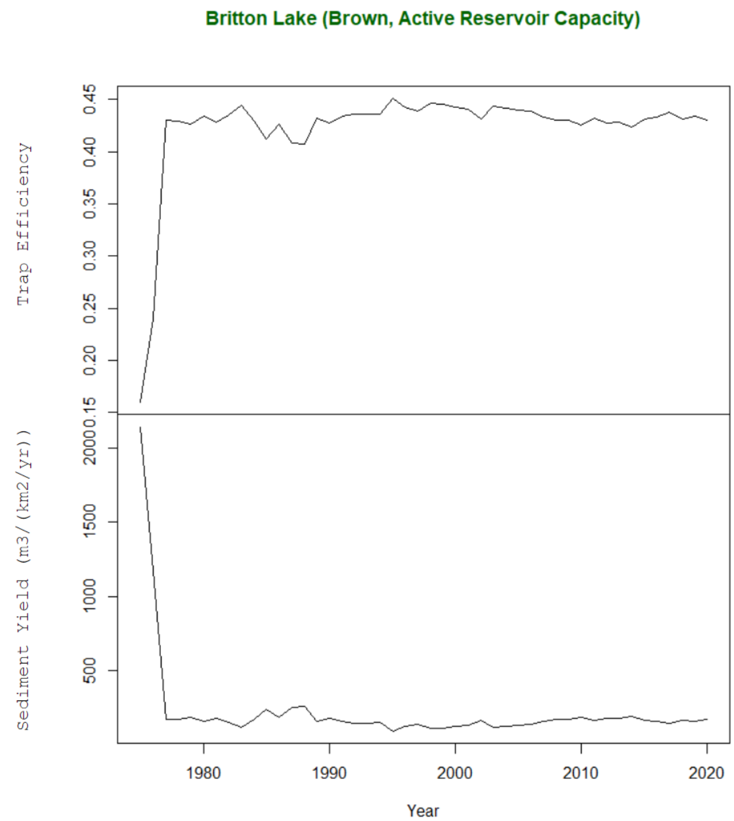

Figure 8. Lake Britton trap efficiency and sediment yield continuous time series using Brown (1944) model.

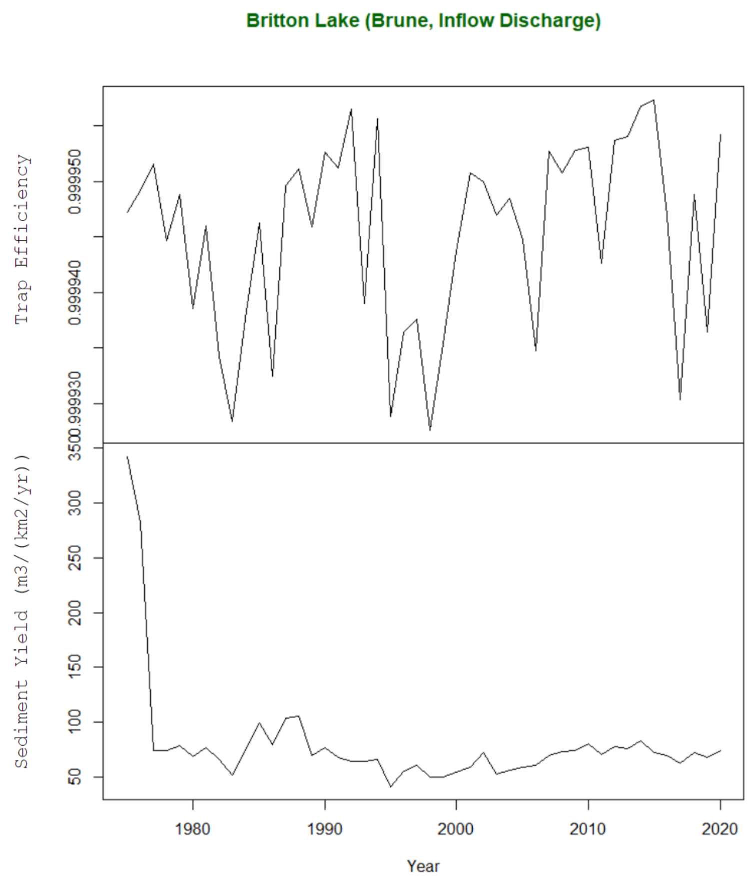

Figure 9. Lake Britton trap efficiency and sediment yield continuous time series using Brune (1953) model.

Table 2. Lake Britton Trap Efficiency and Sediment Yield event occurrence using Rausch & Heinemann (1975) model.

Storm Occurrence Time	Detention Time (Days)	Maximum Inflow Discharge (m^3/s)	Trap Efficiency	Sediment Yield ($m^3/km^2/yr$)
January 1980	3	460	0.700808415	112.8953947
February - March 1986	9	880	0.784012864	126.7335681
April - May 1995	5	430	0.721179027	91.10541183
January - February 1997	8	552	0.760751996	73.06162617
January 2017	7	254	0.724809948	95.98581917
February 2017	8	610	0.763838895	91.08134847
March 2017	10	420	0.771623978	90.1624088

Lake McCloud

At the Lake McCloud site, the Brown model generated the lowest trap efficiency values (Figure 10), and the Brune model generated the highest trap efficiency values (Figure 11). Those trap efficiency values were then used in conjunction with the 3W model to calculate sedimentation yield. The lowest sediment yield values came from the Brune trap efficiency values while the largest sediment yield values came from the Brown trap efficiency.

I couldn't use the Rausch & Heinemann model for this site since I could not find any times/occurrences where the outflow intersects or is close in value to the inflow, thus no detention times could be recorded.

The relationship between the Brown model and its sediment yield calculation is the same shown in Britton Lake, where the trap efficiency and sediment yield exhibited very similar time series shape patterns and the same negative relationship. The Brune model also showed similar results from Britton Lake. The Brune model trap efficiencies were also able to match similar dips, peaks, and trends from the sediment yields; these instances can especially be seen in 1983, 1998, and 2006 (Figure 11). The range of trap efficiency values themselves is more narrow

(0.999945-0.99997) (Figure 4) compared to the values from the Brown model (0.83-0.89) (Figure 10).

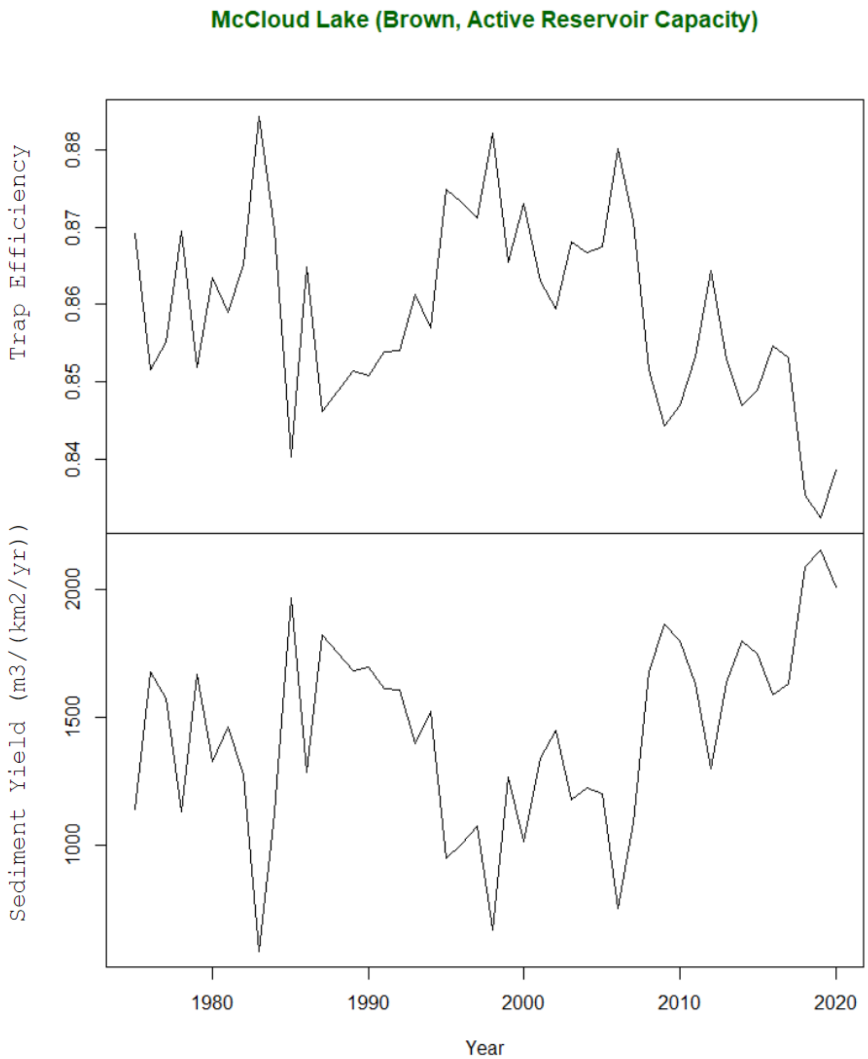

Figure 10. Lake McCloud trap efficiency and sediment yield continuous time series using Brown (1944) model.

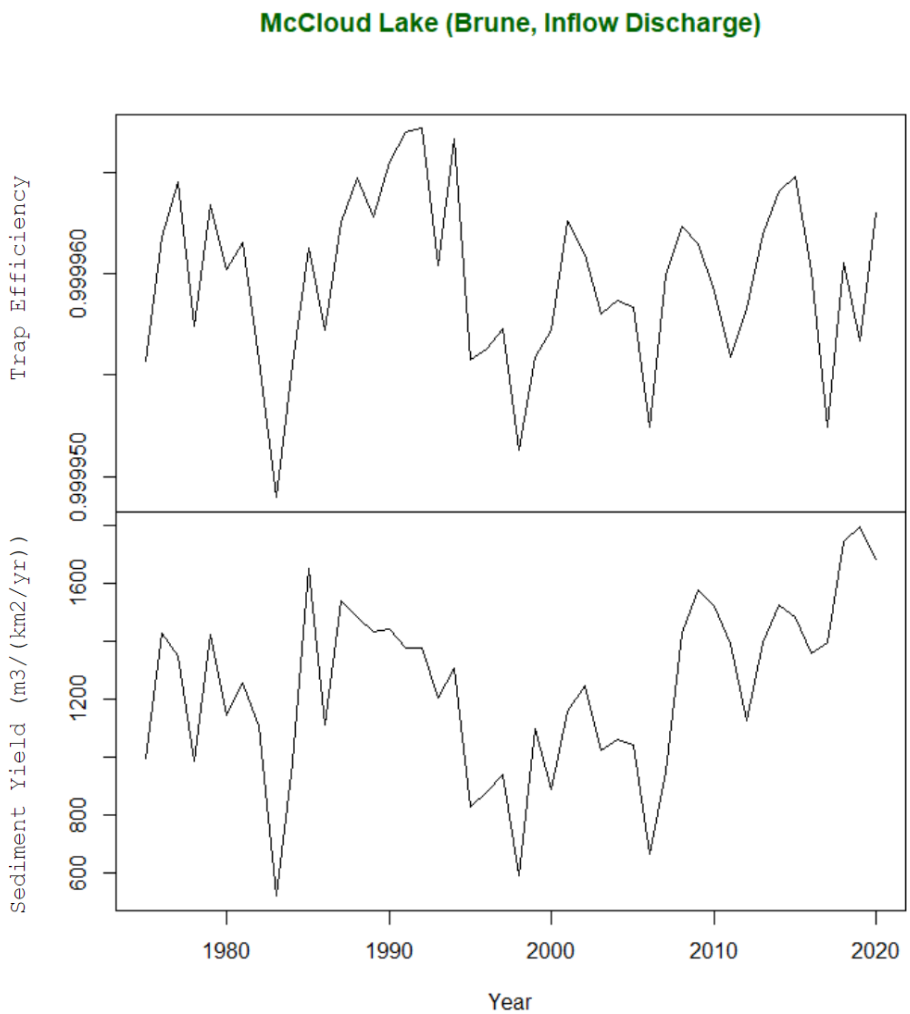

Figure 11. Lake McCloud trap efficiency and sediment yield continuous time series using Brune (1953) model.

Lake Shasta

Shasta Lake trap efficiency values between each model were again, similar to results from Britton Lake and McCloud Lake. The Brown model generated the lowest trap efficiency values (Figure 12), the Rausch & Heinemann models generated moderate trap efficiency values (Table 3), and the Brune model generated the highest trap efficiency values out of all three models (Figure 13). The sediment yield values, however, did not show any significant difference in values: all three models produced sediment yield values within the same range (5000-25000).

The relationship between the Brune and Brown models, and their sediment yield calculation is also aligned with the previous sites. Brown model trap efficiency and sediment yield exhibited very similar time series shape patterns and the same negative relationship. Brune model trap efficiency was able to track increasing and decreasing trends and relative minimum and maximums in sedimentation. The range of trap efficiency values themselves is more narrow (0.99998-0.99999) (Figure 13) compared to the values from the Brown model (0.94-0.99) (Figure 12).

The results from the Rausch & Heinemann model provide a less clear connection between trap efficiency and sedimentation yield. Unlike the previous Britton Lake, the detention time and maximum inflow discharge for different storm occurrences are not always proportionate to each other in all entries: February - March 1986 storm occurrence had the highest maximum inflow discharge but only had a detention time of 7 days, while the February - March 2017 occurrence had 10 days, the longest detention time out of all entries, but only had the second smallest inflow discharge (Table 3). As the trap efficiency for the 1986 was greater than the 2017 event (Table 3), it shows the Rausch & Heinemann trap efficiency model might depend more heavily on maximum inflow discharge than detention time. Between trap efficiency values and sediment yield, there isn't a clear relationship between the two using the metrics from the model.

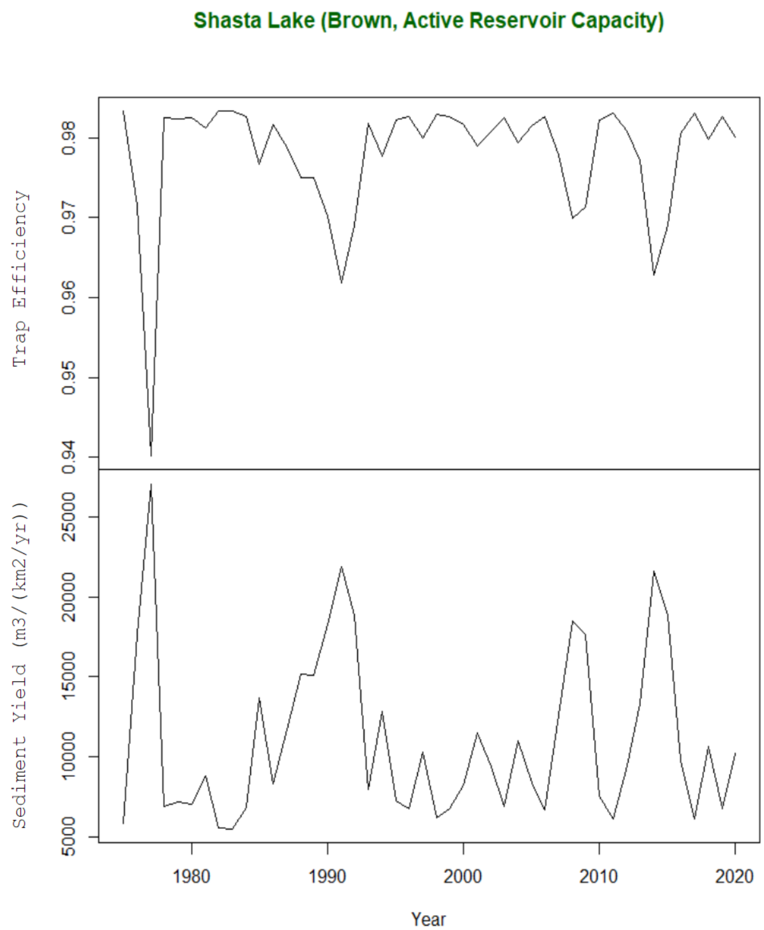

Figure 12. Lake Shasta trap efficiency and sediment yield continuous time series using Brown (1944) model.

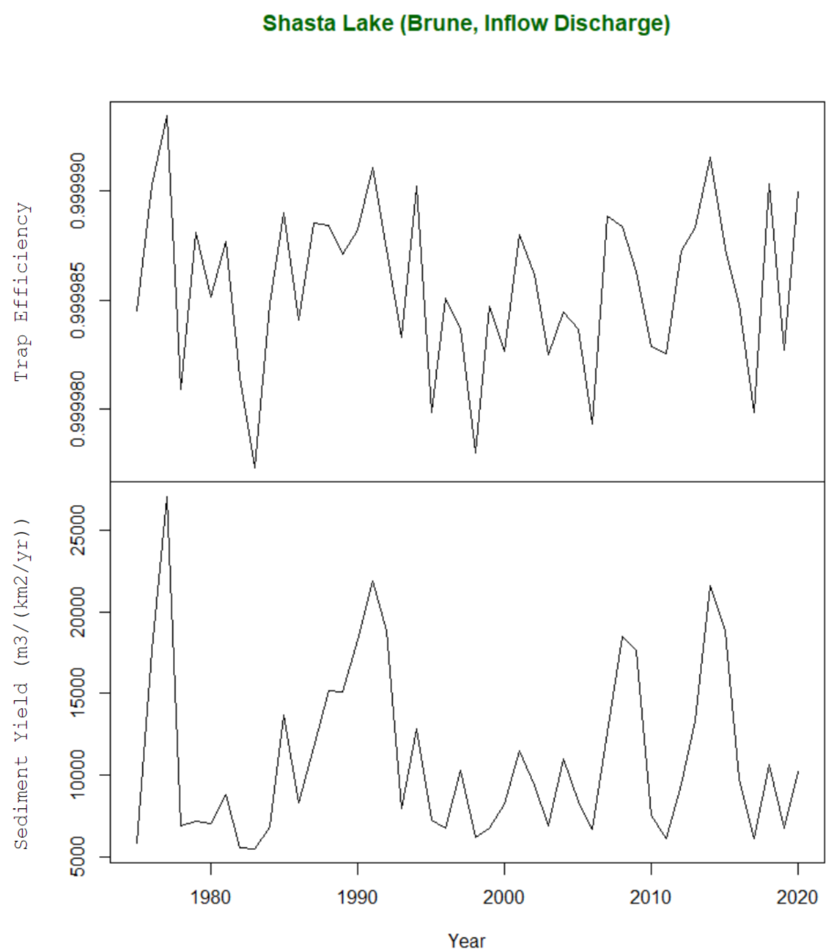

Figure 13: Lake Shasta trap Efficiency and sediment yield, in regards to using 3W upstream trapping sedimentation model, continuous time series using Brune (1953) model.

Table 3. Lake Shasta Trap Efficiency and Sediment Yield event occurrence using Rausch & Heinemann (1975) model

Storm Occurrence Time	Detention Time (Days)	Maximum Inflow Discharge (m^3/s)	Trap Efficiency	3W Sediment Yield ($m^3/km^2/yr$)
January 1980	1	594	0.992538521	7150.00579
February - March 1986	7	1221	0.996125207	13458.95279
January 1996 - February 1997	8	930	0.995309528	6697.954556
February-March 2017	10	920	0.995431832	9651.77155

Comparative analysis reservoir data: how do trap efficiency estimates differ between each reservoir?

Table 4. Averages of Trap Efficiency and Sediment Yield values from 1975 to 2020 in all three sites.

	Britton	**McCloud**	**Shasta**
Average Brown TE Excluding outliers	0.432543032	0.85883885	0.977815188
Average Brune TE	0.999945268	0.999959678	0.999985649
Average Rausch and Heinemann TE	0.746717875	---	0.994851272
Average Sediment Yield ($m^3/km^2/yr$)	134.661	1339.9635	10485.876

Between different reservoir sites, although using the same trap efficiency and sedimentation models, the resulting values and time series patterns varied from each site.

Out of all three sites, Lake Britton had consistently the smallest trap efficiency values in each of the three models, while Lake Shasta had consistently the largest trap efficiency values from each of the three models (Table 4). However the range of trap efficiency values did vary and wasn't consistent from each site. In the Brown models, both McCloud's and Shasta's had only a small window of trap efficiency values compared to Britton's range, nearly five times larger than; the increased range at Lake Britton is probably due to the outlying earlier trap efficiencies as mentioned prior. There aren't any significant outliers like this present in the the McCloud or Shasta sites.

On the other hand, the Brown model trap efficiencies for all sites were much closer in value, almost indistinguishable. Although Lake Shasta had the narrowest Brune trap efficiency range, with Lake Britton having the second narrowest and McCloud having the widest, all their values were around 0.9999 (Table 4), a very high trap efficiency.

The trap efficiency (and in turn, sediment yield) in all three sites all exhibit changing peaks and troughs throughout but even among the three sediment yield time series, there still are some common trends between each series. For example, the Brune and sediment yield datasets in all the three locations all show a steep, relative minimum value at around time step 1983 (Figure 9, Figure 11, Figure 13) . The Brune trap efficiency time series at all three sites also share a similar shape from 2016- 2020 towards the end, where the time series is characterized by a sharp decrease, a sudden increase, another sudden decrease, and another sharp increase ending at 2020.

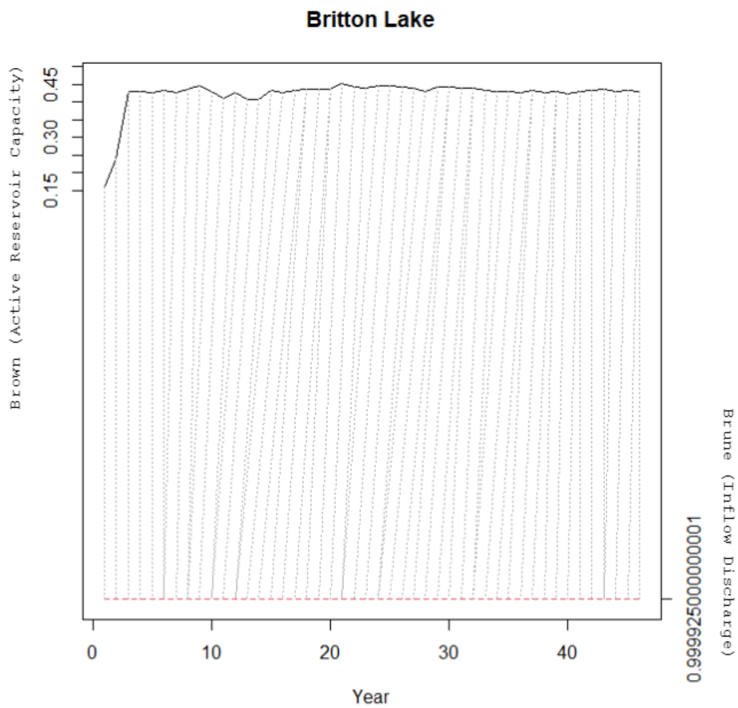

Figure 14. Dynamic Time Warping between Brown and Brune trap efficiency models at Britton Lake.

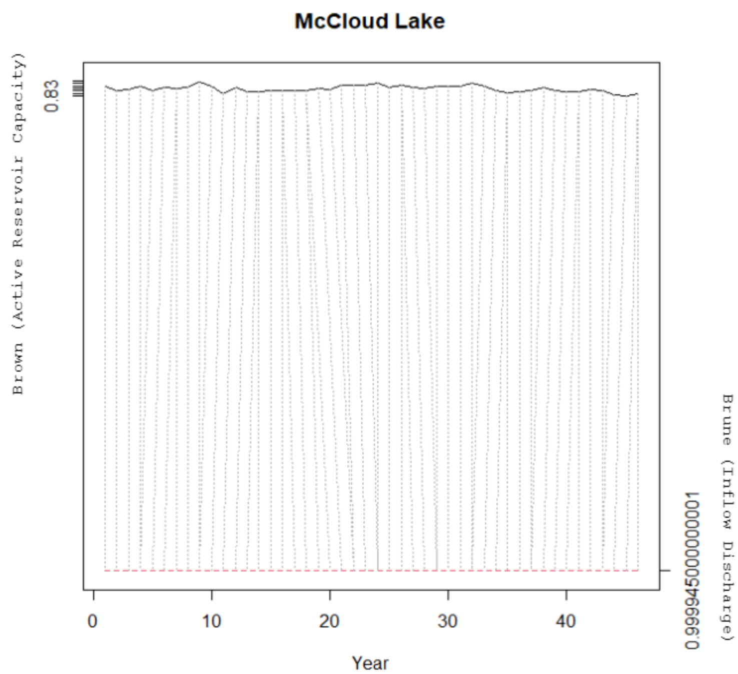

Figure 15. Dynamic Time Warping between Brown and Brune trap efficiency models at McCloud Lake.

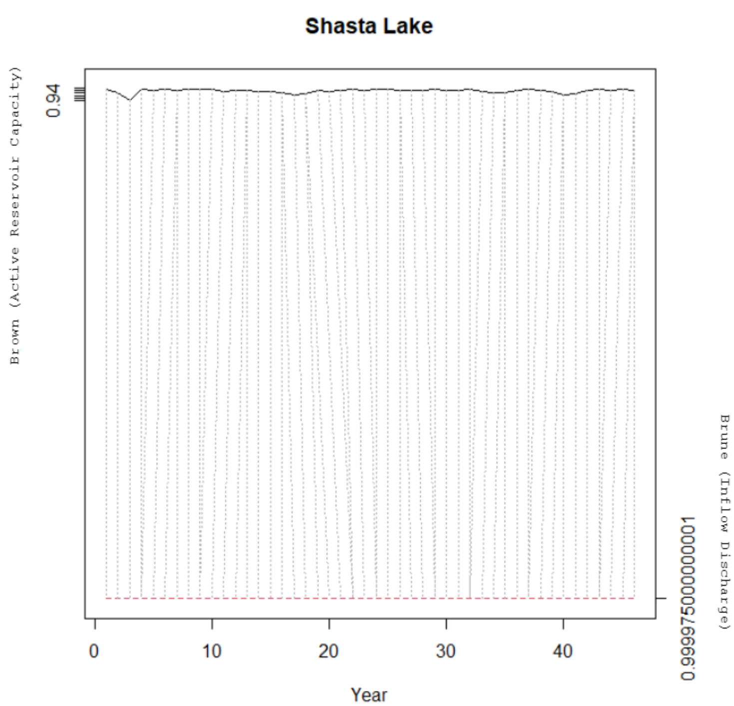

Figure 16: Dynamic Time Warping between Brown and Brune trap efficiency models at Shasta Lake.

In addition, a dynamic time warping algorithm was implemented between the Brown and Brune trap efficiencies to find similar patterns between datasets. Overall for all three sites, trap efficiencies between the Brune and Brown models aligned with each other at their original time step. Britton Lake was, however, the one with the most skewed between models (Figure 14). Trap efficiency patterns from the Brune model seemed to precede over patterns from the Brown model; it's as if trap efficiencies from the Brown model are one time step after the trap efficiencies from the Brune model. All three dynamic time warping charts have many instances where multiple trap efficiencies from one model may fit only one trap efficiency from the other model, and subsequently, instances where one trap efficiency entry may fit into multiple trap efficiency entries from the other model; these are referred to as singularities. From 1975 to 2020, all three sites had 8 instances of these diverging points with both McCloud and Shasta sharing similar timesteps:singularities at years 7, 16, 18, 26 35, 46 in the Brown model and diverging points at years 4, 9, 22, 24, 29 , 32, 37, 43 (Figures 15, 16).

Regression models : which factors influence trap efficiency and reservoir lifetime estimates the most?

From the regressions all Brown and Brune models at each site followed a positive, nonlinear, logarithmic relationship: the dependent variable increases as the independent variable does too. As the independent increases normally, the dependent variable increases at a lower rate. The logarithmic model makes sense since trap efficiency represents the percentage of sediment retention, meaning that trap efficiency cannot exceed over 1. The Rausch and Heinemann models, however, because of their limited number of entries, didn't show a clear relationship between detention time and trap efficiency. There's still a general sense that increased detention time leads to increased trap efficiency, but it seems at some point, for both Lake Britton and Lake Shasta, the trap efficiency at the longest detention time, decreases from previous points.

And because of the lack of data points, unsurprisingly the Rausch and Heinemann model had the lowest r-squared values out of all three models. The Rausch and Heinemann model still showed that there is some association between the detention time and trap efficiencies as both r-squared values are still over 0.5. However, the findings between Lake Britton and Lake Shasta are not the same. Lake Britton's r-squared value was larger than Lake Shasta's, but Lake Shasta had a smaller residual standard error than Lake Britton's (Table 5).

The Brown model produced, on average, the second highest r-squared values among the three models. Lake Britton, even despite previously mentioned outliers, had the highest r-squared value out of all of the three sites, but has the highest residual standard error. Lake McCloud, had a moderate r-squared value but the lowest residual standard error. Lake Shasta has the lowest r-squared but a moderate residual standard error.

This leaves the Brune model as the model that produced the highest r-square values with McCloud being the largest, Britton being the second largest, and Shasta being the smallest.This high r-squared could've been predicted by the small range of trap efficiency values generated seen earlier when looking at the time series. The residual standard error is also significantly smaller than from those from the Brune and Rausch and Heinemann models.

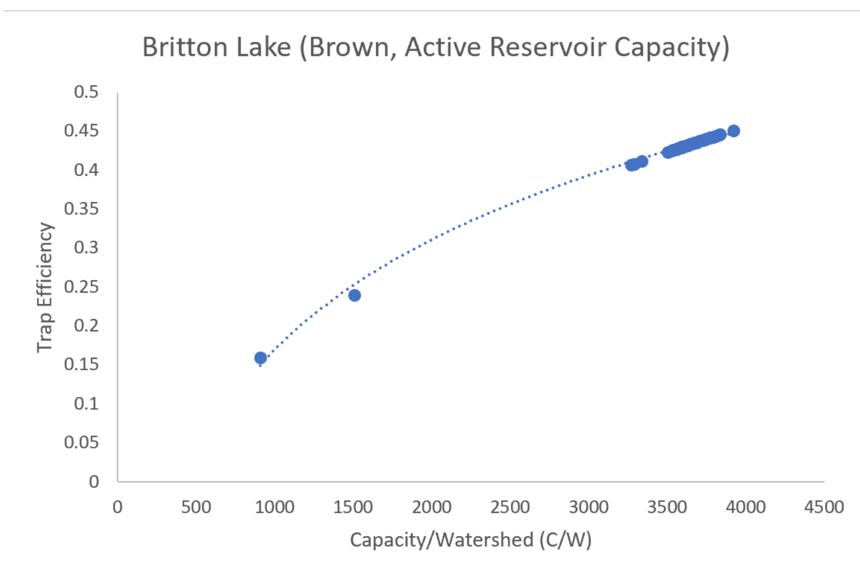

Figure 17: Trap efficiency as related to active reservoir capacity-watershed ratio in Britton Lake.

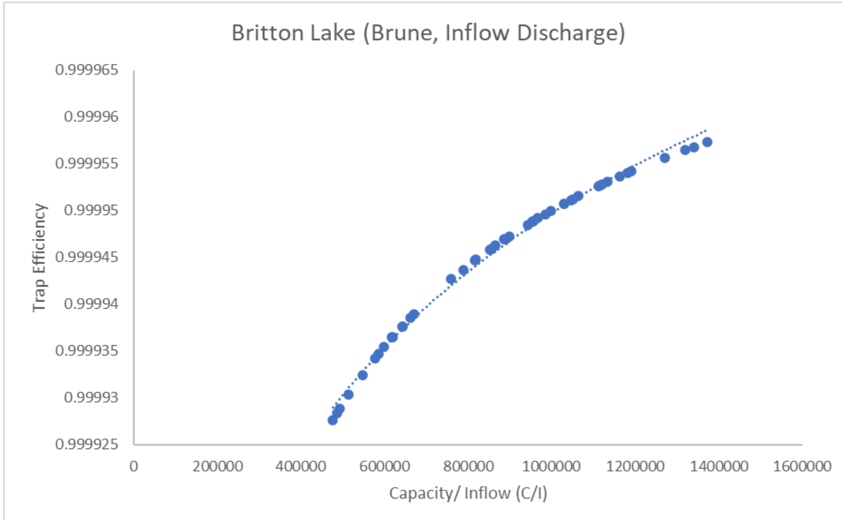

Figure 18. Trap efficiency as related to capacity-inflow ratio in Britton Lake.

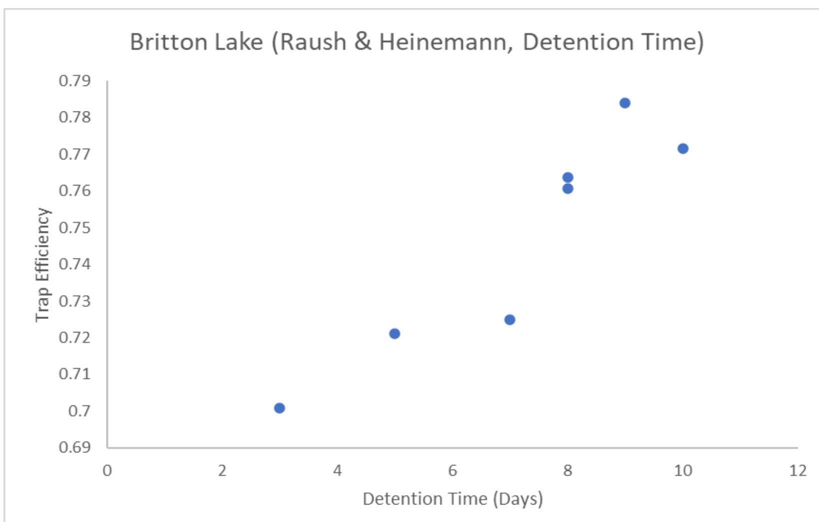

Figure 19. Trap efficiency as related to stormwater detention time in Britton Lake.

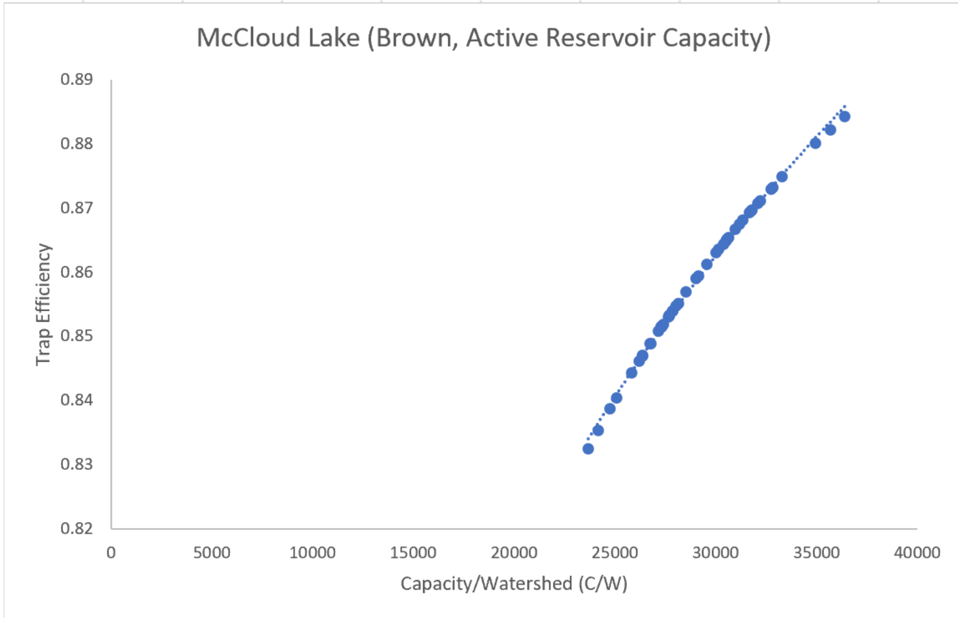

Figure 20. Trap efficiency as related to active reservoir capacity-watershed ratio in McCloud Lake.

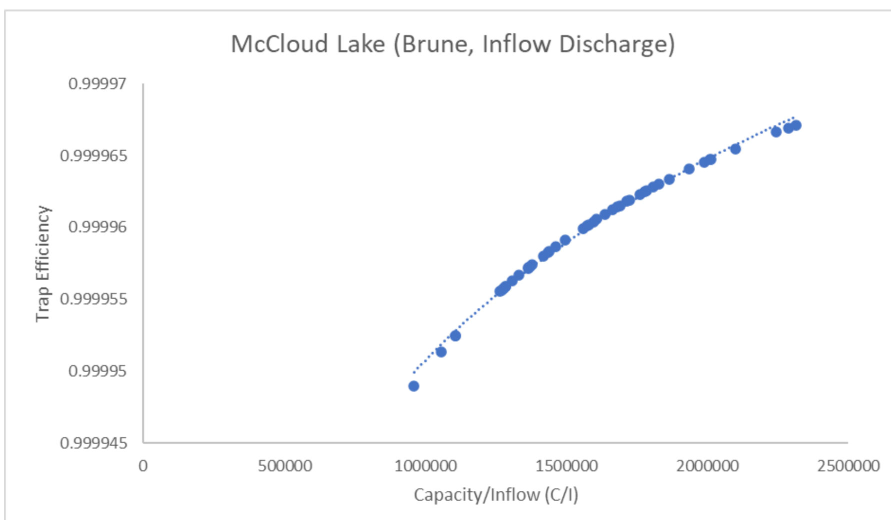

Figure 21. Trap efficiency as related to capacity-inflow ratio in Britton Lake.

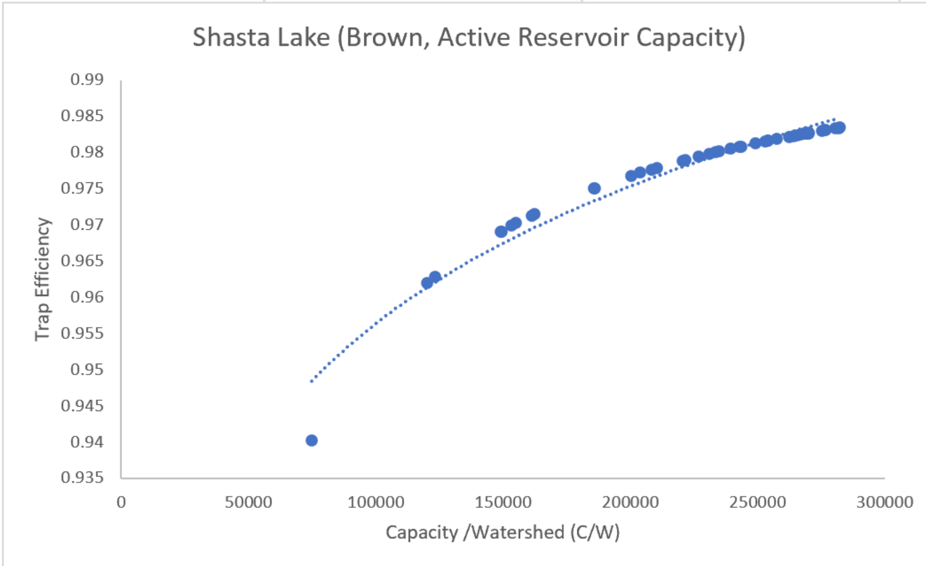

Figure 22. Trap efficiency as related to active reservoir capacity-watershed ratio in Shasta Lake.

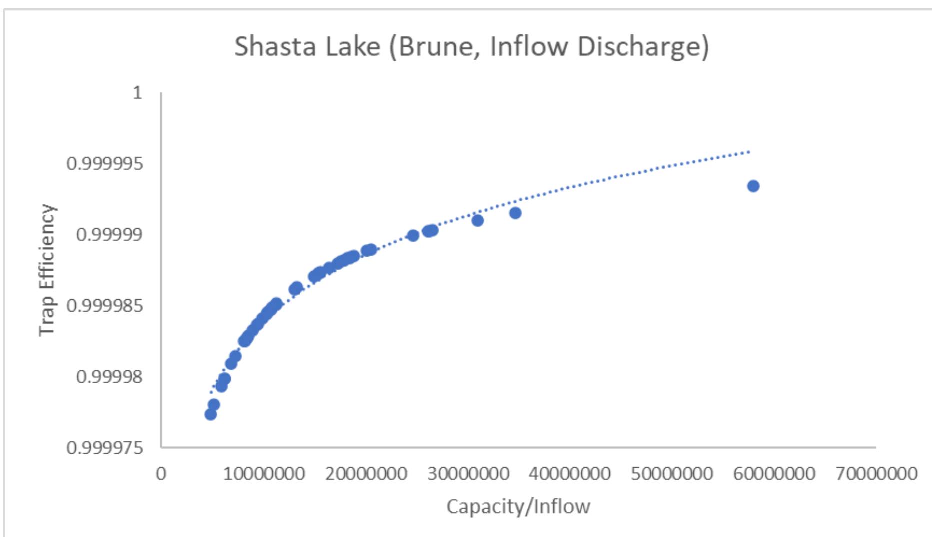

Figure 23. Trap efficiency as related to capacity-inflow ratio in Shasta Lake.

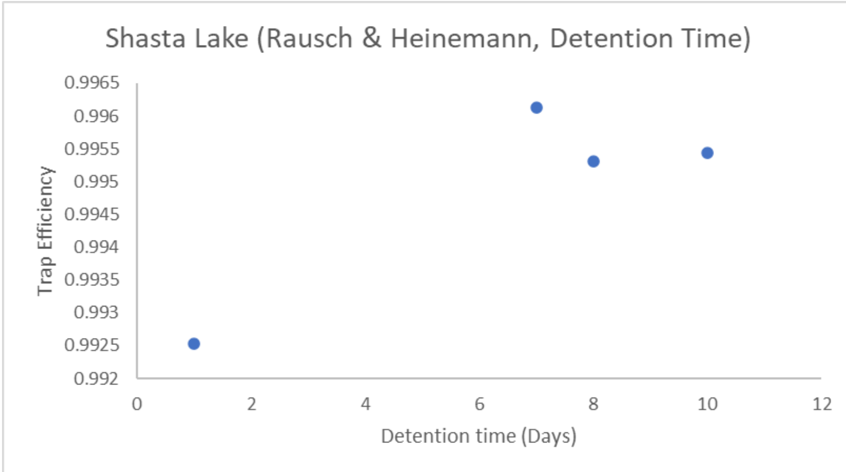

Figure 24. Trap efficiency as related to stormwater detention time in Shasta Lake.

Table 5. Statistics of Regression Analysis for Britton, McCloud, and Shasta Lake.

		Brown	**Brune**	**Rausch & Heinemann**
Britton Lake	R - squared	0.9966	0.9953	0.8613
	Residual Standard Error	0.00432	0.000005	0.01262
McCloud Lake	R - squared	0.9881	0.9957	---
	Residual Standard Error	0.001283	0.000002	---
Shasta Lake	R - squared	0.8552	0.9781	0.6458
	Residual Standard Error	0.003003	0.000005	0.0009422

DISCUSSION

Individual analysis model data: how do different models estimate trap efficiency over time?

The individual reservoir data from each model has provided a range of values, but looking at the difference between the three, there are noticeable overall patterns. The Brown model provided the largest range of trap efficiency values and had produced a very similar shape to the sediment yield time series due to how the 3W model also required active reservoir capacity to calculate. The Brune model provided consistently the highest trap efficiencies between all sites, nearing a value of 1.00, but this high value also meant it provided the shortest range of values. Unlike the Brown (and even the Rausch and Heinemann model), the trends in Brune trap efficiencies were proportional to sediment yield trends. The Rausch and Heinemann model, though to the detriment of unavailable data, could not show continuous time series, but still produced reasonable results, with the trap efficiencies and sediment yields relatively between the lower Brown and upper Brune values. There didn't seem to be a connection between the detention time and the maximum inflow.

Explaining trap efficiency values

For the most part, the trap efficiencies for each site remained the same throughout the 45 year period. The Brown time series for McCloud did show a general decrease in trap efficiency during the time frame, going from 0.87 to 0.84. There are a few times to note. From 1976- 1977, California was hit with a year-long drought (Rettoc and Bortleson 1983). As a result, both the average inflow and active reservoir capacity of the Shasta Dam was reduced by half, leading to a sharp decrease in trap efficiency for 1977 (USGS 2021). McCloud Lake also had their inflow reduced during 1976-1977 which did decrease the average annual inflow; however surprisingly the active reservoir capacity seemed to remain the same (the outflow didn't decrease either) (USGS 2021). This exception could be explained by a unique rainfall event at Redding during the drought (August 14-15, 1976). During that event, rain was pouring in at 2.5 inches/ 6.35 cm per hour; many neighboring towns reported heavy flooding and mud damage in the area (Fontana 1977). Because of extra unforeseen rain, perhaps this is why McCloud was able to maintain their active reservoir capacity. 1975 and 1976 were also the same times where the outliers for Lake Britton using the Brown model showed up. I didn't find out about this until later, but there was a small note on the USGS lake site for Lake Britton, where apparently active reservoir capacity records before 1977 reported usable contents only, explaining the big jump in value for trap efficiency and sedimentation from 1975 and 1976 (USGS 2021). For the rest of the paper, I won't refer to these two years in regards to using the Brown Model at Lake Britton.

There are also other similar trap efficiency patterns in other years. 1983 was also a common time of interest for the Brune time series for Britton, McCloud, and Shasta where all experienced a dip in trap efficiency. Inflow at these sites from 1983-1984 all saw significant increase in inflow during this time, before returning back to their normal levels in 1984 (Current Results 1983). Rausch & Heinemann values in Britton and Shasta Lake also share many event dates, especially noting recent events like the increased rainfall from 2017 that temporarily resolved California's recent mid-2010s drought (Liberto 2017).

Relationship between trap efficiency time series and sediment yield time series

From the data gathered, there seems to be two different ways to calculate sedimentation yield: one that relates trap efficiency and sediment yield negatively like the Brown model, and one that relates trap efficiency and sediment yield positively like the Brune and Rausch & Heinemann models. Trap efficiency is the ratio of incoming sediment trapped by the reservoir to the total sediment inflow (Kondolf 1977). If there was more inflow coming into the reservoir at the first place, there are more chances it can bring sediment in which then increases the chances of those sediment being trapped in the reservoir; metric like having a larger volume of discharge at time or leaving suspended sediment to settle to the bottom for days at a time will definitely increase trap efficiency (Brune 1953). The sediment yield values for both models were also the highest. The Brown model, that uses active reservoir capacity, doesn't have a direct way to calculate the inflow but the amount of actual sediment is known (the difference of sediment from one time frame to another). If the active reservoir capacity is small (less water in the reservoir), the trap efficiency has to be large to explain why the reservoir doesn't have a lot of water and has more sediment (Garg and Jothiprakash 2008).

Synthesis

The calculations for Brown, Brune, and Rausch & Heinemann have shown their own relationships between trap efficiencies and sedimentation yield, and eventual capacity loss. The Brown trap efficiencies are able to calculate sedimentation loss based on the difference in storage volume between set times, able to highlight an accurate range of values; these calculations are best used during normal average conditions in the area with no extreme (weather) events. The Brune trap efficiencies are able to calculate sedimentation based on a set ratio of incoming upstream discharge, able to highlight trends and rate of change; these calculations are best used for extraneous events since Brune trap efficiencies can discern extreme flood or drought very well. The Rausch and Heinemann trap efficiencies are able to calculate sedimentation based on the detention time of sediment; these calculations, like the Brune model, are also good for extreme weather events, especially for rain, with the added benefit of accounting for sediment detention time adding more sediment.

Comparative analysis reservoir data: how do trap efficiency estimates differ between each reservoir?

Although the Lake Britton, McCloud, and Shasta reside within the same Northern California location and same Sacramento river, their trap efficiencies and sediment yields were different even through those 45 years. Out of all three, Lake Shasta has the highest trap efficiencies in all models and sediment yield, with McCloud having the second, and Lake Britton the last. Excluding from being in the same water system although, there might be other factors explaining their difference in values

Reservoir Size

For one, all the reservoirs and dams are built differently. Britton Lake and McCloud lake are similarly sized lakes (Britton Lake has 51,655,000 m^3 while McCloud has 43,400,000 m^3) while Lake Shasta is thousands times larger than both reservoirs (5,614,800,960 m^3). In terms of global standards, Lake Britton and McCloud are medium-sized reservoirs while Lake Shasta would be a large one (Wisser et al. 2013). One study looking at reservoirs throughout the globe however suggested that smaller dams are likely to lose reservoir capacity at a faster rate (due to sediment gain in volume) while larger dams have smaller reservoir storage loss rates, with assumption that larger reservoirs are more downstream and thus sediment is trapped upstream. For reservoirs at sizes of 10^6 and 10^8, the annual loss rates were actually quite similar, both under 2% (Wisser et al. 2013). Quickly calculating loss rate from average sediment yield (multiplied by drainage area) and total storage capacity, the loss rates were higher ranging from 2.7-3.2% percent loss rates, but still within reasonable range.

Reservoir location

The location of where the reservoir is upstream or downstream relative towards each other. The large volume of water in the Sacramento river is due to the many tributaries that combine into the main path. The Pit river and the McCloud river are the two uppermost streams in the Sacramento river, which then all three merge towards Shasta Lake where the now larger river continues to move south. Because Lake Britton and Lake McCloud are upstream from Lake Shasta, sediment can get trapped from the Pit 3 and McCloud dam. This has led other studies to either believe the trap efficiency for the next dam downstream would either decrease since the upstream dams would filter out the sediment (Wisser et al. 2013) , or increase since clearer water may increase the potential energy of the water which would cause further bank and channel incision, actually bringing in more sediment (Kondolf 1977). I did two calculations with the 3W model at Shasta Lake using both $R_{c,t}$, which only accounted for data Shasta data above, and $R_{b,t}$ which accounted for upstream sediment volume upstream (and also the one used in the Results section) (Minear and Kondolf 2009). As a result, the $R_{b,t}$trap efficiencies and sediment yield values were smaller than those calculated from $R_{c,t}$, showing the first conjecture was true for this case. Smaller trap efficiencies due to upstream tracking could also explain the difference between Lake Britton's and McCloud's different trap efficiency values despite their similar drainage area and reservoir size. Recall that Lake Britton is formed by the Pit 3 dam, which is part of a whole system of similarly named dams owned by PG&E throughout the Pit River. There is a Pit 1 Dam still in operation upstream which imposes its own sediment trapping and flow regime.

Reservoir operation

The Pit 3 Dam and McCloud Dam, and by definition Lake Britton and Lake McCloud, are both run by PG&E for hydroelectric power. The Shasta Dam and reservoir are run by the United States Bureau of Reclamation for flood control, power generation, irrigation, and recreation. Dam operations won't necessarily control the actual trap-efficiency of the reservoir (especially if trap efficiency is calculated from inflow) but still can play a role with the amount of sediment that may be kept or released/removed in the reservoirs.

While average outflow of the Pit 3 Dam has fluctuated between 2 m^3 per second to 68 m^3 per second during a year, the McCloud outflow has been steadily rising from 3 m^3 per second to 6 m^3 per second in recent years (USGS 2021); the increase in McCloud might be a response to regulating environmental flow regulations towards the douglas fir and cedar trees below (Hesseldenz 1981). If these two upstream streams have increased their outflow, this would cause an increase in Shasta's inflow and trap efficiency. The Shasta reservoir operates its outflow differently from the other two, in which case, instead of maintaining a constant ratio of inflow to outflow for an entire year, the Shasta reservoir significantly increases its outflow during the summer months (USGS 2021).

As for any actual sediment record kept, reflective of Podolak's and Doyle's (2015) work on looking at the number of sedimentation surveys across US reservoirs, there hasn't been many studies done on these three sites (Podolak and Doyle 2015). I was able to find one 2009 study commissioned PGE that looked at the channel geomorphology around the McCloud river: they calculated a sediment yield of 480 $m^3\ km^{-2}\ yr^{-1}$, but they did account for more than trap efficiency with historical and current bathymetric surfaces and bulk sediment in their calculation (Nevares and Stallman 2009). There was also a study done by USGS that briefly looked at sediment movement, but was mainly focused on suitable biological/chemical conditions for benthic organisms (Fontana 1977). The lack of sedimentation reports for each of the dams limits not only current understanding, but limits the information needed to manage sediment in the future. This is especially concerning for big and important dams like Shasta Dam; there's been discussion of dredging the Shasta reservoir, but most people speculate on the high costs and effort as a main hurdle (Beauchamp 2015).

Synthesis

Although trap efficiency is calculated with factors like active reservoir capacity, inflow, and detention time, a reservoir may have other intrinsic properties unique to itself that also impacts the trap efficiency, sediment yield, and storage loss. Smaller reservoirs are more susceptible to holding more sediment since they tend to be more upstream and have less upstream trapping.

The results from my study also suggest that more upstream locations would have higher trap efficiencies and more downstream locations would have smaller than usual trap efficiencies. The reduction in trap efficiency due to upstream trapping, however, isn't completely contradictory to Minear and Konoldf's findings. Because water needs enough potential energy in order to start incising channel banks and sides, it's possible the water from Lake McCloud and Lake Briton may not have traveled far enough for ther to be any noticeable increase in trap efficiency at Lake Shasta (Kondolf 1977).

Human intervention and reservoir management may help in reducing sediment by suggesting such measures like upstream erosion control, dredging, or re-routing sediment to different pools in the reservoir (Fan and Morris 1992), but there haven't been enough (recent) studies for all of these three sites individually or as a whole to make a decision in sediment management.

Linear regression: how well do factors predict trap efficiency?

Each trap efficiency model at each location was fitted in a regression model. The Brown and Brune curves both were able to fit into non-linear regression models from their measured metric (active reservoir capacity, inflow discharge) and trap efficiency. Rauch and Heinemann did not have a lot of data points; it would be meaningless to try to fit a regression model. All three though, did have high R-Squared values with the inflow discharge and the Brune trap efficiencies resulting in the highest R-Squared value at all sites; Brune standard residual error was also the smallest. Brown had the second highest R-squared values, and Rausch and Heinemann the smallest; there wasn't a noticeable relationship between r-squared values and standard residual error for these models though. McCloud lake had the highest R-squared values while Shasta lake had the lowest R-squared values.

Brown: active reservoir capacity

Active reservoir capacity was used as the main calculation for trap efficiency since sediment volume could be calculated from it. In Brown's study, a positive logarithmic relationship between the capacity-watershed and trap efficiency was calculated. Brown's relationship means that a larger active reservoir storage would result in higher trap efficiencies. The calculations and relationship done between capacity-watershed and trap efficiency also show a positive logamatic relationship, matching the Brown curve's calculations.

Brune: upstream discharge

Brune's original study looked at 44 reservoirs around America, finding a large range of different numbers for trap efficiency. Most of the flood control reservoirs had trap efficiency values of 0.1-0.6, but some sluicing and desilting operations also have a chance of decreasing trap efficiency, at max, by four fold. Out of the 44 reservoirs, there were two from California reservoirs surveyed (represent); these are the Bullard's Bar from the Yuba River North Fork (which is another Sacmramento tributary) and the Pardee dam in the Mokelumne River (Brune 1953). Their average C/I ratios were 0.0378 and 0.313 and their trap efficiencies were 0.78 and 0.95. The capacity inflow ratios (> 1) for this study (and by default, the trap efficiencies) was much higher than these two results, resulting in much higher trap efficiencies for all three of reservoirs. If the capacity inflow is too large, this either means that the total built capacity was somehow bigger than it should be, or the inflow values were too small. In the earlier methods, this error should've been mitigated by multiplying inflow values by the drainage area of the reservoir, especially for McCloud and Shasta, but still produced C/I's much bigger than the averages in the Brune study.

The calculations and relationship done between capacity-inflow and trap efficiency also show a positive logamatic relationship, matching the Brune curve's calculations.

Rausch & Heienemann: stormwater detention

There were Missouri three dams measured in this Rausch and Heinemann for their relationship between detention time and trap efficiency. The three reservoirs in the Rausch and Heinemann had less storage capacity than the reservoirs in this study. Two of the Missouri dams surveyed had similar drainage area and total capacity while the third one was much smaller than the other two. However the trap efficiency values were 0.82, 0,85, and 0.79 (Rausch & Heinemann 1975). The regression coefficient between detention time and trap efficiency was 0.61, 0.86, and 0.76. The regression coefficients from Lake Britton and Lake Shasta were in the same range: 0.8613 and 0.658. Large detention times and high maximum inflow would increase trap efficiency.

Synthesis

All three factors have strong prediction relationships towards trap efficiency. The Brune model did the best job in predicting trap efficiency and having data points match up closer to the regression model. Although both the Brown and Brune curves showed the same positive logarithmic relationship, their factors that make up the models affect the trap efficiency in contradictory ways. Increasing active reservoir capacity increases the trap efficiency, while increasing inflow actually decreases trap efficiency.

Limitations and future directions

As said earlier in study, and to the dismay of many other researchers, a big hurdle for calculating sedimentation values is the lack of public info available for general or public; this goes for the quality of data, the amount of data, and currency of data. One of the most well-known sedimentation databases is known as the The Reservoir Sedimentation (RESSED) Database, owned by USGS, that has records of 7,752 surveys of national dams ranging from 1754 to 2021 (Podolak and Doyle 2015). However, a majority of the entries in the database are old, non-digitized, lacking further analysis, or a combination of the three. Still, the effort put into RESSED is commendable, and it’s still being updated and renovated today by many passionate advocates.

The USGS WaterData site, although carrying much more recent data, doesn’t actually have sedimentation records, thus why researchers need to use such metrics like active reservoir capacity, inflow, or outflow to make even an estimate for actual sedimentation data. The California WaterData site houses nearly 7643 records of different stream or lake gauging sites throughout the state (USGS 2021). Even then though, some of the information about the sites are still a bit disorganized; for example, like the discrepancy in active reservoir capacity in Lake Britton as mentioned earlier in discussion. There's also a lot of other opportune gauging sites that could record valuable information needed, like the knowing actual total inflow for Lake sites (Minear and Kondolf 2009) without having to refer to more upstream gauging sites.

As for limitations in my study design itself, I did overlook a lot of aspects once my results came out like not accounting for non-continuous values in Rausch & Heinemann or faulty data in Lake Britton's active reservoir capacity. I did wish to make a modification on the Dynamic Time Warping algorithm that might match the points between Brown and Brune trap efficiencies better. As recalled in the results, there were a number of singularities present in both Brown and Brune time series at all sites that converged and diverged multiple for different points. These converging/diverging singularities are the results of a difference in variability between y-value ranges between the sets. Instead, a *Derivative* Dynamic Time Warping algorithm could've been used. In normal Dynamic Time Warping, a difference would be calculated using the actual values of the entries, but in Derivative Dynamic Time Warping, it finds the difference between local derivatives (Keogh and Pazzani, 2001).

Broader implications

California is one of the largest and lucrative states in the United States. As a home for millions of people, it's important that there's enough water for everyone's basic needs and societal infrastructure. However it seems California's water supply (or rather lack of) gets worse every year. Although others are turning to other alternative water sources from recycled streams or the ground, surface-level water reservoirs still hold the greatest supply. But because the water is on the surface, connected to the rest of the rivers and environment, this leads to sediments getting trapped within the reservoirs.

From this study, it seems that most trap efficiencies over time have remained within the same range throughout the last 45 years. This could be seen as good since the values haven't been increasing, but could also be seen as unfortunate since they're not going down.

But how could someone even decrease the trap efficiency? From the results from models, it's concluded that both a larger active reservoir capacity and a smaller inflow would lead to an increased trap efficiency. By the same logic, that means a smaller trap efficiency would be achieved by having a smaller active reservoir storage but high upstream inflow. In a region known for droughts, having a small active reservoir capacity is not good. And if active reservoir capacity were to increase again, this would have to in turn, increase trap efficiency. Perhaps, it might be natural for reservoirs to have relatively high trap efficiency values because of this if it means there still is water for the rest of California.

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