Assessing Indicators of Stream Health in the Tuolumne Watershed

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Abstract

The Tuolumne River watershed, ranging from Yosemite National Park in the high Sierra Nevada mountains to the central valley floor, contains multiple dams that provide a range of services from water supply and hydroelectric generation to recreation. We studied the impacts of these dams on the Tuolumne river ecology by assessing a series of stream health indicators in regulated and unregulated portions of the watershed. Data was collected on channel bed substrate distributions, algal biomass, benthic macroinvertebrates, and fish assemblages as indicators of overall stream health. Our findings indicate that dams, and especially daily pulse flows released below the dams, alter the variables for which we collected data. We provide some information on the costs and benefits to environmental flows in the Tuolumne River and suggest management of water releases below dams can be shaped to sustain essential ecosystem functions, without severely altering the economic and water delivery benefits. Implementing changes to the flow regime that will benefit the ecosystem, such as better mimicking the characteristics of the spring snowmelt recession or limiting pulse flows to the appropriate high flow season, is attainable and affordable within the Tuolumne watershed.

Introduction

The Tuolumne river watershed lies in the southern portion of the Western slopes of the Sierra Nevada and encompasses 1,958 square miles. There are four dams within the watershed primarily used for hydroelectric power, recreational flows, and a steady water supply during California's dry summers. Though dams provide many social and economic benefits, essential processes of the watershed are impeded, including the ability for sediment and aquatic species to migrate through the river system (Null et al., 2014 and references therein). We studied the impacts these dams have on the river ecology by assessing a series of stream health indicators in regulated and unregulated portions of the watershed.

The watershed can be broadly split into three sections based on geology: upper, middle, and lower (Epke et al. 2010). O'Shaughnessy dam marks the delineation between the upper and middle river sections, while New Don Pedro Dam separates the middle and lower sections of the river. The Tuolumne River in Tuolumne Meadows is an unregulated, snowmelt-dominated system in the high country of Yosemite National Park. The middle section, also known as the mainstem Tuolumne River, receives flows from Holm Powerhouse on Cherry Creek and is characterized by regulated daily summer pulse flows. Tributary to the mainstem Tuolumne is the Clavey River, the largest unregulated river in the watershed. Though the Clavey has a lower stream order than the mainstem Tuolumne, it serves as a good comparison to better understand the impacts of varying flow regimes. The lower Tuolumne River, which begins below New Don Pedro Dam, has been severely altered by agriculture and dredging that took place in the early 20th century, and has a modified flow regime focused primarily on water delivery in summer. We compared stream health indicators from the unregulated upper Tuolumne and Clavey River with indicators from the regulated mainstem and lower Tuolumne to determine potential impacts on stream ecology from altered flow regimes.

We choose four primary indicators of stream health that reflect biotic productivity, species diversity, and physical habitat conditions. Algal biomass, in the form of Ash Free Dry Mass (AFDM), was calculated as a proxy for primary productivity. Benthic macroinvertebrate diversity, represented by the percentage of Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa, was calculated as an indicator of water quality and resource availability. Fish surveys were used to determine native and non-native species presence, and an assessment of the substrate size distribution of the channel bed was used to indicate in-stream habitat conditions, as sediment size is a key factor in most aquatic species life history strategies.

In unregulated Sierran river systems, native aquatic species are adapted to the seasonal flow regime (Figure 1). The peak flow during snowmelt at the start of the spring recession in snowmelt-dominated systems results in the dislodging and scouring of in-stream gravel (Yarnell et al., 2010). When subsequent flows decrease slowly to baseflow, gravel and sediment in transport deposits, resulting in well-sorted, clean channel bed substrate available for aquatic succession. Regulated daily pulse flows, on the other hand, flush suitable spawning gravel and fine sediment downstream with each pulse, while dams upstream trap replacement gravel. On the mainstem Tuolumne River, large pulses are released every summer morning from the Holm Powerhouse for recreational whitewater rafting (C. Graham, personal communication) (Figure 2). These pulses potentially lead over time to channel armoring and a lack of finer substrate in the downstream river reaches.

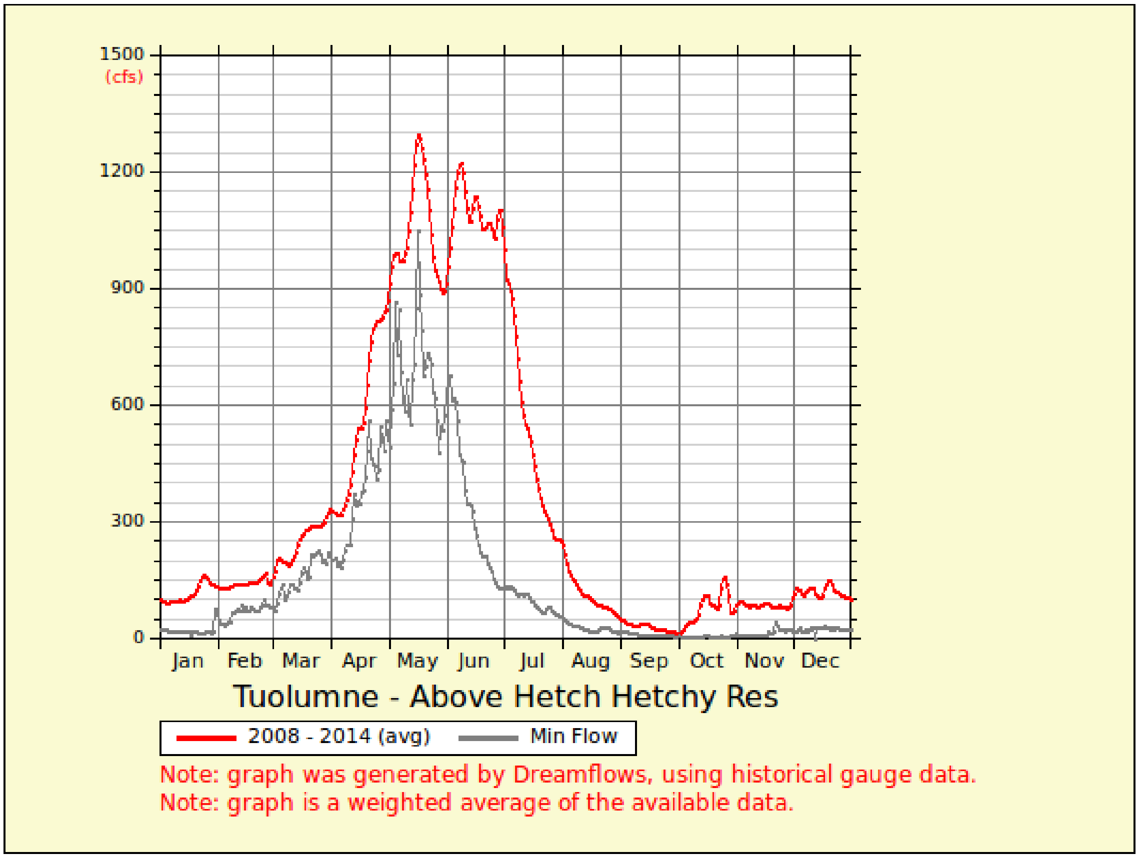

Figure 1. Typical unregulated snowmelt-dominated hydrograph occurring in the upper reaches of the Tuolumne River (Dreamflows 2014).

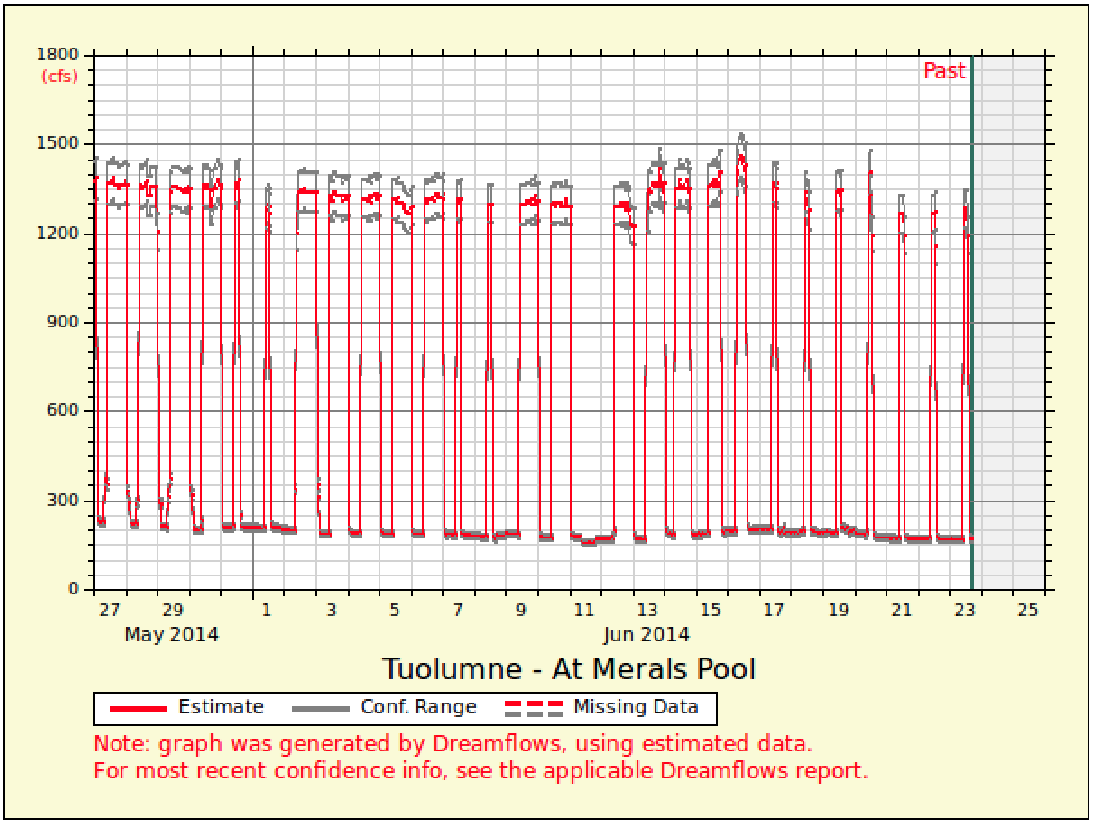

Figure 2. Daily fluctuation in flows in the mainstem Tuolumne River at Merals Pool (whitewater recreation put-in) (Dreamflows, 2014).

The daily pulsed flows in the mainstem Tuolumne River also create a highly variable flow regime with significant daily change in habitat conditions. The high rate of change in the daily pulsed flows differs from the more gradual slow rate of change in flow that occurs in unregulated systems. In unregulated rivers, slow rates of change in flow during the spring snowmelt recession sort gravel and sediment into a greater variety of instream habitats that support a greater diversity of species (Yarnell et al., 2010). The gradual transition from high to low flow creates the essential disturbance, erosion, and deposition patterns responsible for necessary abiotic habitat, such as shallow gravel bars used for fish reproduction and floodplains used by macroinvertebrates (Peterson, 1996; Milhous, 1998; Osmundson et al., 2002). A high rate of change in flow results in decreased habitat availability over time as flows move rapidly from a flood to baseflow state. In regulated systems with daily pulse flows, hydraulic habitats continually vary and shift over the daily period making it difficult for less mobile species such as macroinvertebrates or juvenile fish to move with the changing habitat.

Due to impacts from decreased sediment availability and variable flow regimes, we hypothesize that river reaches below dams will have fewer positive indicators of stream health. We also hypothesize that the mainstem Tuolumne where daily pulsed flows occur will have the most impacted conditions as measured by the indicators.

Methods

In order to assess stream health in each of the three primary sections of the Tuolumne River, we collected data on instream habitat (substrate composition), primary and secondary productivity, and presence of native and non-native fish species.

Channel bed substrate composition was determined by standard Wolman Pebble Counts (Wolman 1954), where at least 100 particles were randomly sampled in each reach. Median grain size was determined with a gravelometer ranging in scale from <2 millimeters (mm) to >256 mm. The totals for each phi-size category were then aggregated.

Algal biomass was gathered by randomly selecting five rocks in each reach and collecting 1 in^2 of algae from each. The algae samples were composited and stored in a cool dark area to prevent reproduction. Once in the lab, samples were filtered through a microfiber filter, dried for 24 hours, and then weighed to obtain total dry mass. Samples were then burned and weighed to determine the ash-free dry mass (AFDM). AFDM was subtracted from the total dry mass to determine the total algal biomass. We also compared algal data collected one month prior to this data collection to determine potential changes density over that time period.

Benthic macroinvertebrate composition was determined via standard kick-net procedures (Barbour et. al. 1999). Three cross-sections were randomly selected along the length of the sample riffle, and five kicks were completed in equi-distance locations along each cross-section. Substrate from a 1 square foot area directly in front of the net was thoroughly mixed by hand or foot for 30 seconds, and the contents were then aggregated into a bucket. Each cross-section sample was then sorted and identified into orders and families. The percentage of EPT taxa was determined by summing the number of individuals from each of the three orders and dividing by the total number of individuals sampled.

Fish presence surveys were completed through snorkel surveys, seining, and observations from boats and on land. Snorkel surveys were conducted by two observers swimming a 10 meter longitudinal section of the sample reach while reporting fish observations to a recorder. A 10-meter seine net was used on suitable beach habitat on the Clavey River as well as the lower Tuolumne. Two group members pulled in the seine while another identified and recorded the fish sampled. Species seen while in boats or while on land were also recorded as part of the total fish composition observed.

Results

Channel Bed Substrate Composition

Our data showed channel substrate in the mainstem Tuolumne was skewed towards large sediment, with fewer finer particles (Figure 3). Tuolumne Meadows and Clavey River showed a broad distribution dominated by mid-sized particles and fewer large particles. The lower Tuolumne also showed a broad distribution of sediment sizes but with fewer finer particles than the Clavey or Tuolumne Meadows.

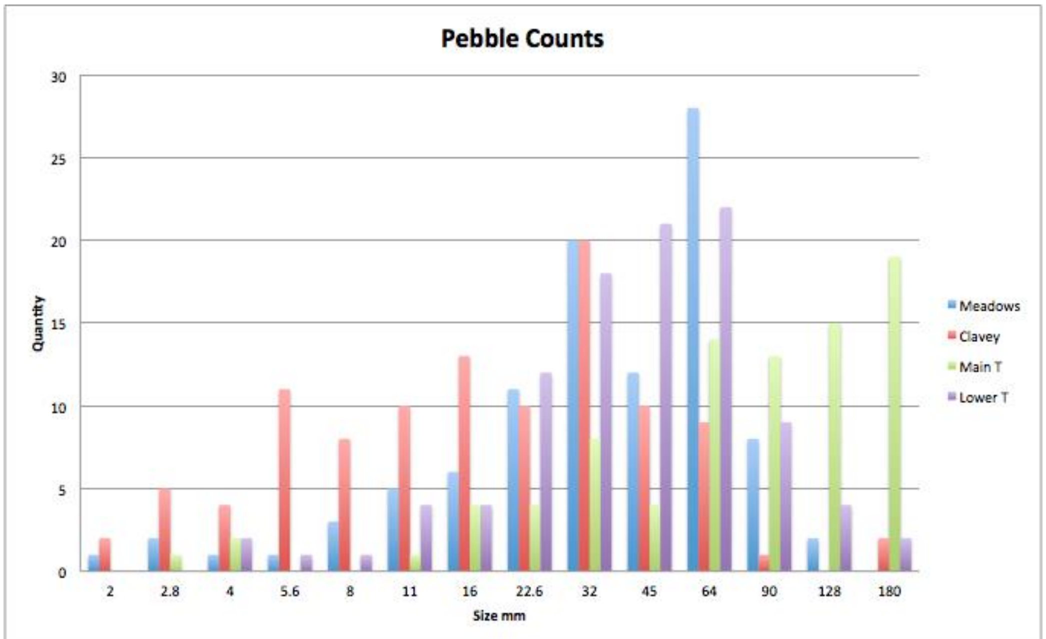

Figure 3. Channel bed substrate size distribution for each of the four study reaches in the Tuolumne River. From upstream to downstream in the watershed, study reaches are: Meadows (blue), Clavey (red), Mainstem Tuolumne (green) and Lower Tuolumne (purple).

Algal Biomass

The highest algal biomass was observed in the Mainstem Tuolumne River, upstream of the confluence with the Clavey River (Figure 4). The Clavey River showed moderate levels of algal biomass, relative to the other sample sites, and showed a large increase in production between May and June. Tuolumne Meadows had the lowest algal biomass of the sites.

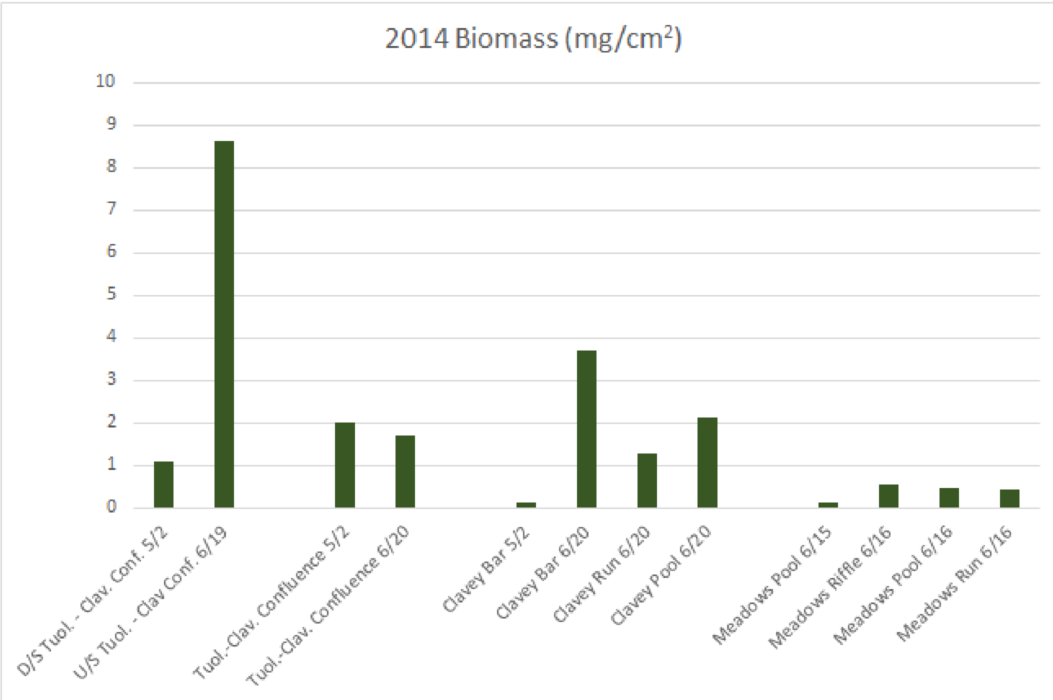

Figure 4. Algal biomass at each study site in Tuolumne Meadows (right), Clavey River and the mainstem Tuolumne. The Lower Tuolumne was not sampled for algae. The mainstem Tuolumne and Clavey River sites were sampled in May and June.

Percentage of EPT taxa

Tuolumne Meadows had the highest percent of EPT taxa, 88% , among the sampled reaches (Figure 5). In the mainstem Tuolumne, the percent of EPT taxa was lowest, with 16% sampled upstream of the Tuolumne-Clavey confluence and 19% downstream of the confluence. The Clavey River and Lower Tuolumne had similar percents of EPT taxa, 64% and 62%, respectively.

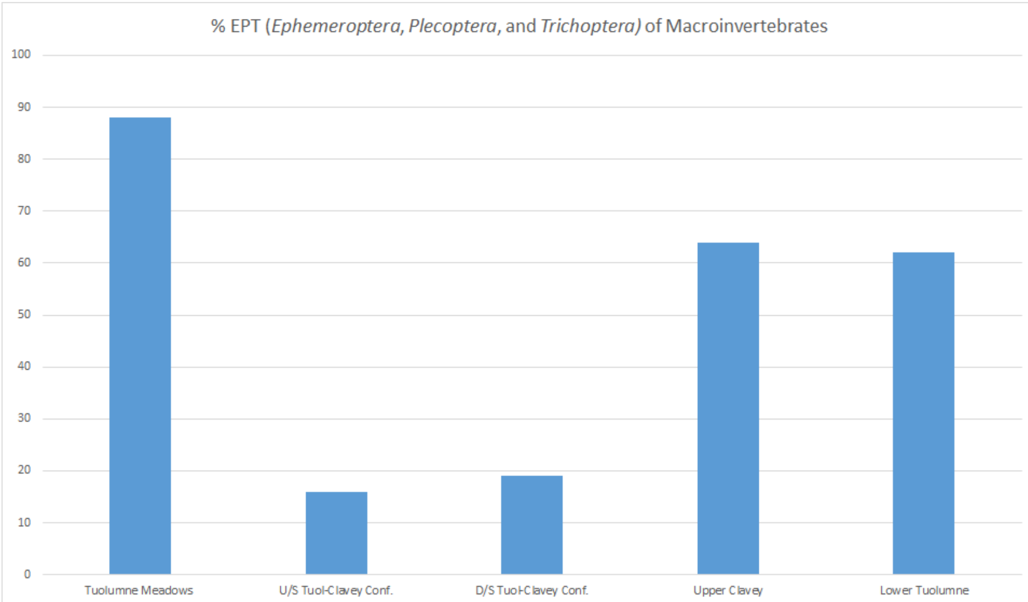

Figure 5. Percentage of EPT taxa sampled in each of the study reaches. Tuolumne Meadows (right) is the most upstream site.

Fish Assemblages

Rainbow, brown, and brook trout were observed in Tuolumne Meadows. On the Mainstem Tuolumne and Clavey Rivers, Sacramento pikeminnow and rainbow trout were observed. In the Lower Tuolumne below New Don Pedro Dam, Sacramento pikeminnow and Chinook salmon were seined, while Bluegill, Smallmouth Bass, Largemouth Bass, Mosquitofish, Common carp, and Sacramento suckers were observed.

Discussion

Indicators of Stream Health

Channel Bed Substrate Composition

The channel bed substrate is a key factor for fish reproductive success in that many native species require gravel-sized substrate for spawning, with the exception of the Sacramento pikeminnow, which are broadcast spawners. Adult rainbow trout, Chinook salmon, and Sacramento pikeminnow migrate upstream to spawn, and search for habitat suitable for egg fertilization and incubation, as well as areas providing safe development and growth of post hatched larvae. Typically eggs are released and fertilized in gravel-dominated areas with low flow, sufficient dissolved oxygen levels, and appropriate temperature. Rainbow trout often find these properties at the head of a riffle or the downstream edge of pools (Workman et al. 2004).

In the Tuolumne watershed, substrate composition varied between study reaches. In the unregulated reaches (Clavey River and Tuolumne Meadows), abundant gravel-sized material was observed within a broad distribution of sizes. On the mainstem Tuolumne, the distribution was skewed to larger sizes with few smaller particles and limited gravels. These findings support the idea that regulated daily pulse flows push finer sediments downstream at a higher rate than finer sediments can enter, resulting in coarse armored channel beds. Recurrent high magnitude and high rate of change flows also may prevent material from being well-sorted. In contrast, on the unregulated reaches, a wide range of sorted material was observed throughout the study reaches, likely due to higher sediment supply and a natural flow regime. On the lower Tuolumne, abundant gravel-sized material occurred, likely due to anthropogenic restoration activities such as gravel augmentation below the dam.

Algal Biomass

Algae are a primary food source for many types of biota in the Tuolumne watershed. Benthic macroinvertebrate scrapers and collectors, including stonefly and mayfly larvae, consume mainly algae, and in turn become a stable food source for the damselfly larvae, one of the many benthic macroinvertebrate predators in the watershed. Larval and juvenile stages of rainbow trout, Chinook salmon, and California pikeminnow feed on macroinvertebrates, which often are living in the algae, and although adult rainbow trout dominantly feeds on benthic macroinvertebrates, they have been found to consume algae (McAfee 1966, Raleigh 1984). Algae are most nutritious in the early growth stages, so streams where algae is consistently getting dislodged and replaced has a higher nutritional value for the benthic macroinvertebrates that rely on it. Aquatic trophic levels rely on a natural balance of primary production and primary consumption, which is why a healthy algae population is important to the watershed.

Algal densities in the upper and lower reaches of the watershed were found to be similarly low, lending evidence to a higher rate of turnover and regrowth. In the mainstem Tuolumne, the differences in algal biomass between upstream and downstream of the Clavey River confluence, although they were measured one month apart, were large compared to the Clavey River over the same time period. This was possibly due to sediment added by the Clavey River, which increases scour of material below the confluence. Above the confluence, there is lower potential for sediment movement and scour from finer material. Additionally, the mainstem Tuolumne has been invaded with *Didymosphenia geminate* (Didymo), an invasive non-native algae that is not as nutritious for the primary consumers as the native algae (James, Ranney et al. 2010). Didymo grows in large mucilaginous stalks that have a high biomass but lower nutritive value for species. The high biomass values observed on the mainstem Tuolumne likely reflect the presence and abundance of Didymo.

Percentage of EPT taxa

The percentage of EPT taxa in benthic macroinvertebrate samples provides an indicator or measure of water quality. EPT taxa are sensitive to pollutants and low dissolved oxygen levels, so high quality streams generally have the highest species richness of these orders (Phillips 2005). Conversely streams with higher pollution or more impacted conditions will have lower percentages of EPT taxa. The high percentage of EPT taxa sampled in the unregulated reaches of Tuolumne Meadows and Clavey River support the idea that these reaches have suitable instream habitat conditions that are less impacted than the reaches sampled in the mainstem Tuolumne. Daily dam-released pulse flows can wash away benthic macroinvertebrates through repeated cycles of catastrophic drift (Epke, 2010), and thus are likely contributing to the low numbers of sensitive taxa observed in the mainstem Tuolumne.

Fish Assemblages

Native fish species often have very specific habitat niches in which they can survive, and changes in the environment can quickly change the fish assemblages seen in streams. Thus fish composition can serve as an indicator of stream health in many river systems. Niche partitioning of fish can be based on temperature, food availability, flow, and spawning availability, each of which can be changed downstream of dams. In streams with flow and instream habitat most similar to the natural or undammed conditions, we expect the proportion of native species to non-native species to be higher.

In unregulated Tuolumne Meadows and Clavey River reaches, 100% native species were observed as expected due to more natural flow conditions. However, in the mainstem Tuolumne, 100% native species were also observed, contrary to our expectation. The mainstem study reach at the Clavey confluence is over 10 miles upstream of New Don Pedro reservoir, where many non-native fish reside. It may be that many of these non-native reservoir species cannot reach the Clavey confluence due to flow or habitat conditions. In the lower Tuolumne reach however, below New Don Pedro Dam, a much higher number of alien species was present, along with several native species. In this portion of the watershed, flow regulation and changes to instream habitat may make the lower reach more suitable to alien species.

Dam Economics

The data collected in this study demonstrates some of the known impacts of dams on aquatic habitat, biota and stream health. However, dams also have economic effects that can often overrule the importance of the health of the system. Controlling of water has been an objective for thousands of years, but construction of large dams became more common in the 1930s. As a result, most of the major rivers in the world are dammed. Dams were originally built for human development. They provide a reliable source for drinking and agricultural water, hydropower, recreational benefits, navigational help, and flood protection (Brown et al., 2009).

While dams are most often associated with positive effects on humans or negative effects on the ecosystem, they also have negative effects on humans. Dams can disrupt the economy and culture of the area in which it was built by forcing people to move. Additionally, if a dam fails, it could lead to the widespread destruction and death of individuals downstream (Brown et al., 2009).

Building dams today has not been as prominent as it was in the mid 1900s. Dam removal is becoming a more desired option for increasing economic benefits. Removal of dams has to be evaluated on a site by site basis as some are more beneficial than others. It has been found that some dams may be removed without reducing economic costs. Removing dams may also mean that the dams that are still there are relied upon more (Null et al., 2014).

This does not necessarily mean dam removal is the only solution. Dam removal eliminates all of the aforementioned positive benefits as well as the negative impacts. In this particular case in the Tuolumne River Watershed, removal of O'Shaughnessy Dam has been shown to be feasible with little water scarcity but with high costs for removal. Costs arise from having to filter water to maintain quality and a loss from hydropower generation revenues of about $12 million a year. The water from O'Shaughnessy Dam has filtration avoidance, which makes it very valuable to the San Francisco Public Utilities Commission, the operator of O'Shaughnessy Dam (Null & Lund, 2006).

The Tuolumne River is also dammed further downstream by New Don Pedro Dam. San Francisco has a water bank storage agreement with Modesto and Turlock Irrigation Districts to store water released from O'Shaughnessy Dam (Null & Lund, 2006). Removal of New Don Pedro Dam would be significantly harder as it is bigger than O'Shaughnessy Dam and supplies water to many more customers. New Don Pedro Reservoir can hold 2,030,000 acre feet of water for use by the Modesto and Turlock Irrigation Districts and can generate up to 203 megawatts of power (Turlock Irrigation District, 2010). Due to the size and importance of New Don Pedro Dam to the surrounding areas, removal has not been considered like the removal of O'Shaughnessy Dam.

Even when dam removal is possible, whether a dam is removed or not comes down to economics and politics (Null & Lund, 2006). Dam removal on the Tuolumne River in the near future does not seem likely; however, improving the health of the river may be achieved by improving management for environmental flows.

In California it is estimated that stream restoration costs about $6 million per 1000 km of rivers (Null et al., 2014). Stream restoration costs also vary depending on type of restoration, such as whether restoration is for aesthetics or for storm water management. Bernhardt et al. (2005) found stream restoration projects that focused on flow modification had a median cost of $198,000. Improving environmental flows to better mimic a natural flow regime is shown to have a big role in improving the whole river ecosystem (Rheinheimer et al., 2012).

While many economists will ask for a specific value to the benefits of mimicking a natural flow regime, ecological benefits are difficult to quantify and have no agreed upon value. Costanza et al. (1997) estimated global ecosystem benefits to be worth at least 33 trillion in 1994 U.S. dollars. For lakes and rivers in particular, the value estimated was $8,498 1994 U.S. dollars per hectare per year (Costanza et al. 1997). At over 1,958 square miles the Tuolumne Watershed is one of the largest watersheds in the San Joaquin system, which makes it difficult to exactly quantify what ecosystem services an improved flow regime would produce (Epke et al., 2010; The San Francisco Public Utilities Commission, 2014). While estimating ecosystem benefits has its advantages there are numerous variables, therefore the remainder of this analysis focuses on costs to changing the flow regime.

Currently, during wet years, the streamflow from O'Shaughnessy Dam is somewhat similar to unimpaired flow. However, differences include loss of winter floods, lower winter maximum daily average flows, faster increase in ascending snowmelt streamflow, lower snowmelt peak flow magnitudes, shorter and steeper snowmelt recession streamflows, and higher than natural summer and fall base flows (Figure 6) (The San Francisco Public Utilities Commission, 2014). Better mimicking natural flows to limit these differences would not dramatically affect water storage and would be much less than the cost of removing the dam. Any excess water needed could come from water contracted from New Don Pedro Reservoir.

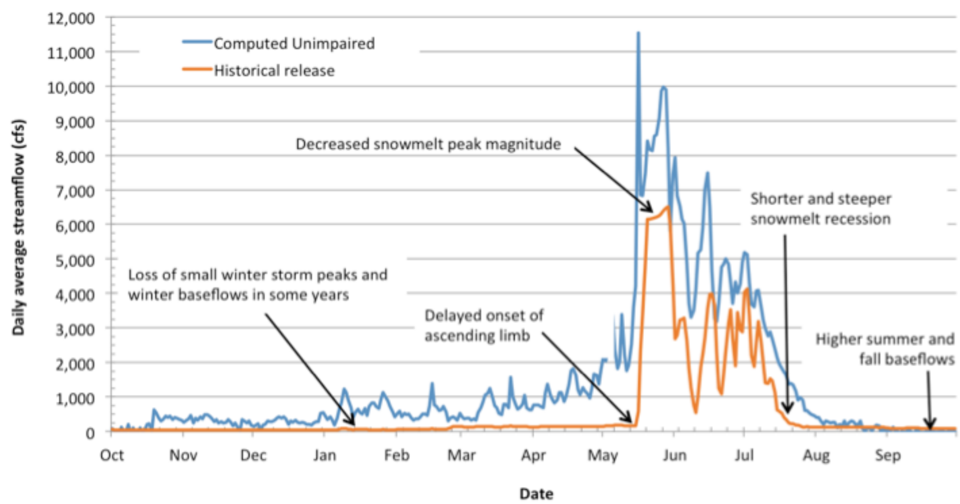

Figure 6. Unimpaired and historical release flows from O'Shaughnessy Dam (The San Francisco Public Utilities Commission, 2014)

Due to flow regime changes below O'Shaugnessy dam, there are warmer flows in the winter and colder flows in the summer than would naturally occur. These conditions benefit cold water species such as trout but have negative impacts to species such as the Foothill yellow-legged frog and western pond turtle (The San Francisco Public Utilities Commission, 2014). Changing the flow regime would come at a cost to the trout, but at a benefit to other less common native species. A decrease in trout would alter recreational fishing as trout are often fished for.

For benefits to be accrued throughout the mainstem Tuolumne, flow regime changes would also need to occur below Holm Powerhouse on Cherry Creek, a tributary to the mainstem Tuolumne. Holm Powerhouse receives its water from Cherry Lake and Lake Eleanor. Flows are released daily to generate hydropower, and in the summer months for four hours per day to provide boatable flows on the Tuolumne River for recreation. This creates an unnatural flow regime that has daily pulsed flows with impacts to sensitive aquatic species (Figure 2).

If it were not for the recreation, San Francisco Public Utilities Commission (SFPUC) would optimize their hydropower revenue by releasing flows during optimal peak times for energy generation. It is estimated that SFPUC is sacrificing about $20 million per year by releasing flows for recreations. If SFPUC were to mimic a more natural flow regime instead, there would likely be the added benefit of energy generation during peak municipal use (C. Graham, personal communication).

Generating electricity by mimicking natural flow regimes typically does not result in a significant change to revenue. Rheinheimer et al. (2012) found that increasing minimum instream flow requirements and imposing a maximum down ramp rate would have a marginal effect on revenue generated in the Upper Yuba River Watershed. A 75% increase in minimum instream flow would only come at a 2% cost of revenue from hydropower. Even when impacts from global warming and the potential decrease in water supply were taken into account, the most ecologically beneficial instream flow requirements would result in less than a 7% loss of revenue. While these values would not directly correlate to the Tuolumne River Watershed, likely losses in revenue due to environmental flow modifications would be relatively limited. In the Tuolumne watershed, revenue may actually increase if a more natural flow regime is implemented as the current daily releases for recreation is not economically most beneficial for SFPUC.

Releasing flows from Holm Powerhouse that better mimick a more natural flow regime would come at a cost to recreation and the boating community. The boating season would be more variable and shorter because there would not be flow releases throughout the summer in most years. Only two commercial companies can launch on the mainstem Tuolumne River per day, each with two to three paddle boats with four to six paddlers per raft for a total of 16 to 36 rafters per day (Whitewater Rafting Guide to River Trips, 2014). The rafting season typically comprises three to four months from May through August, amounting to 92 to 122 operational days each year (All-Outdoors California Whitewater Rafting, 2014). At a cost of $239 per person per day, the revenue generated from rafting is estimated between $0.35 million to $1 million per year. Assuming a loss of boatable flows in July and August under a more natural flow regime, roughly half of this revenue may be lost in some years.

In the Tuolumne River, mimicking a more natural flow regime would not result in water lost as New Don Pedro reservoir would capture water released from dams upstream. Some loss in water quality for water delivered to San Francisco may occur, but the cost of treatment might be partially offset by increased revenue from hydropower generation. Relative to the high costs of removing a dam, implementing changes to a more natural flow regime is an economically feasible for obtaining substantial river ecosystem benefits.

Conclusion

Our evaluation of data collected throughout the watershed on various indicators of stream health suggests that dams are having an effect on the Tuolumne River watershed. Below O'Shaughnessy Dam and Holm Powerhouse on the mainstem Tuolumne where daily pulse flows dominate the flow regime, changes in channel bed substrate distribution, algal biomass, and percentage of EPT taxa were observed. The data showed that the unregulated Clavey River was more similar to Tuolumne Meadows in terms of stream health than to the immediately adjacent mainstem Tuolumne. The lack of regulation on both of these river reaches likely explains this similarity, although other factors not specifically measured in this study could be contributing. While we found some differences between the unregulated reaches and the regulated Lower Tuolumne, primarily in fish assemblages, the Lower Tuolumne was more similar to the unregulated reaches than to the mainstem Tuolumne. This may be due to the on-going restoration efforts to restore gravel-sized substrate, establish more natural instream habitats and create a more natural flow regime. In particular, the lack of daily pulse flows on the Lower Tuolumne likely provides more stable and predictable hydraulic habitat for aquatic species. Based on the data collected, we suggest that the dams and regulated flow regimes in the Tuolumne River system are influencing the river ecosystem in ways that are measurable and quantitative. With current water demand and California's Mediterranean climate, dams are necessary. However, management of water releases below dams can be shaped to sustain essential ecosystem functions, without severely altering the economic and water delivery benefits. Implementing changes to the flow regime that will benefit the ecosystem, such as better mimicking the characteristics of the spring snowmelt recession or limiting pulse flows to the appropriate high flow season, is attainable and affordable within the Tuolumne watershed.

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