# Drought Responses of the Tuolumne River Ecosystem

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The Tuolumne watershed is exemplary in California's water history for the diverse services the river provides. A changing climate, entwined with the Euro-American settlement of the Sierra Nevadas, has and will continue to change the way species in California use water. New trends in precipitation patterns and river responses will likely tend toward extremes as the climate warms. Decreasing snow-packs and lower stream flows during summer in the Sierra Nevada Mountains attest to this trend. The effects of an altered flow regime over a year, or ten, of the Tuolumne River are of particular importance for the City of San Francisco. The San Francisco Public Utilities Commission [SFPUC] operates a reservoir in the Hetch Hetchy Valley that collects clean mountain stream-water for its residents almost year round. A few times during the year, extremes in flow patterns induce changes to the water quality, increasing sediment and particulate matter influx into the stream, and the water must be filtered before being delivered to customers. Water quality changes that occur in response to drought conditions affect the in-stream communities as well as humans. This paper reviews literature on the effects of drought on the inputs to headwater stream systems like the Upper Tuolumne River. Both during and after drought, changes in the stream-upland fluxes propagate through aquatic taxa and degrade ecosystems. However, the changes that drought inflicts on stream health have minimal effects on the quality of the water stored in the Hetch Hetchy reservoir.

**Hetch Hetchy Valley**

The geology of the high Sierra Nevada Mountains lends itself to good water quality. The granite over which the Upper Tuolumne tributaries flow produces very little sediment, except during large flow events (Epke et al. 2010). The clean water of high Sierran streams can also be attributed to the cool, steep environment that inhibits high productivity of benthic algae. The geologic history of the mountain range's formation also led to an abundance of gold deposits in the granitic rock that drove Western pioneers to claim and carve up the land (Epke et al. 2010). Hetch Hetchy Valley's notoriety in American society came out of these pioneering expeditions, and its shape and clean water were soon recognized as a prime setting for a reservoir. Despite public outcry, prior inhabitance by Native Americans, and its inclusion within the Yosemite National Park, the valley was flooded, and O'Shaughnessy Dam was operational in 1934. Since then the reservoir has provided hydroelectric power and exceptionally clean water to the residents of San Francisco, needing minimal filtration and chemical treatment. However, many still push for its removal (Null and Lund 2006). San Francisco's reliance on this reservoir for water supply necessitates an understanding of the factors that provide such clean water, in order to assess the risks of degraded water quality in the face of a changing climate and the possibility of more frequent critically dry periods in California.

**During Drought**

Periods of lower than average precipitation levels are expected to increase in severity in the coming years (IPCC, 2013). Increases in the magnitude and frequency of droughts will result in declining summer streamflows as warmer air temperatures increase forest-water uptake, decreasing surface runoff (Tague and Peng 2013). Diminishing stores of water dry out soils and slow groundwater recharge. Groundwater input into streams in the Sierra Nevada is crucial for maintenance of base flow throughout the arid summer season; declining groundwater levels in response to higher evapotranspiration and earlier snowmelt threaten the availability of water in the summer months. Hyporheic inputs into a river are also an important source of chemical nutrients (Boulton et al. 1998). Drought and a warming climate both induce low flows in rivers, and biotic and abiotic processes respond accordingly.

Sediment and particulate loads in the stream experience a change when the transport capabilities of the streamflow decrease. When there is little regular overland runoff, as is commonly the case during droughts, the influx of particulates, both inorganic and organic, decreases. Allochthonous sources of coarse particulate organic matter accumulate on the land's surface rather than moving into the stream. A study of trees in Yosemite National Park during a multi-year drought found increased mortality rates in three species of trees (Guarin and Taylor 2005). A similar effect on other vegetative taxa is likely due to less soil water availability, resulting in higher deadfall and leaf senescence rates. Upland forest communities are more susceptible in periods of drought to severe fires due to the increased fuel production. After such a fire occurs, the particulate load stored on the ground surface increases dramatically. During periods of little rain, the accumulated detritus stored on the ground does not reach the aquatic community because there is no overland flow to wash the material into the stream. Sediment load in the stream decreases as a result of low flows, and slow moving flows deposit material on the streambanks (Mazurkiewicz 2011). Overland flow is a crucial component of stream health, bringing particulate matter, large woody debris and sediment into the stream. In periods of drought, the typical balance of energy, habitat and disturbance is disrupted.

New patterns in flow regime and particulate influx will alter the assemblage and abundances of organisms living in and around a stream. Many species living in the Tuolumne river system are adapted very specifically to California's current seasonal flow cycle. Low streamflows and decreased woody debris inputs decrease habitat availability. Habitat reduction decreases both macroinvertebrate and fish populations, resulting in more aggressive resource and niche competition (Bunn and Arthington 2002). Benthic algae populations produce more biomass as more light reaches the streambed, and increased temperatures promote faster growth (Lake 2003). Microbial populations will initially respond to the influx of detritus from macroinvertebrate and fish die off, as well as the increase in algal biomass. Warm stream temperatures also speed up microbial metabolism rates. In places of low gradients, such as the upper reaches of the reservoir, increased microbial activity depletes dissolved oxygen in the stream and increases the level of dissolved organic carbon [DOC] (Lake 2003). Low levels of dissolved oxygen are responsible for further declines in fish, macroinvertebrates, and even macrophyte populations.

During times of drought, the Upper Tuolumne River is likely to experience degradation of its aquatic ecosystems in response to lowered streamflows. However, the water that reaches Hetch Hetchy reservoir, by human standards, is relatively unimpaired. Water temperature and dissolved oxygen do not affect drinking water quality, and decreased sediment inputs benefit water supply managers. Increased dissolved organic carbon [DOC] levels can negatively impact drinking water quality as interactions with disinfecting treatments can create harmful byproducts. However, the magnitude of change in DOC concentrations once the water reaches the City of San Francisco's treatment system is not very large. Thus, Hetch Hetchy's water quality is at minimal risk for the changes that occur during drought years.

**Post-Drought**

When increased precipitation relieves a drought, the overland runoff flushes the material stored on the ground surface and dry banks into the stream, resulting in changes in sharp increases in particulate organic matter composition. Sadro and Melack (2012) studied the effects of a large autumn storm event on a Sierra Nevada lake. They found that the extreme rainfall event replaced organic material produced in the lake with allochthonous material washed in from the surrounding hillslopes resulting in a nearly fifty percent decrease in primary productivity after the flow receded. The lake also exhibited a marked decrease in oxygen levels as increased decomposition occurred shifting the entire lake towards heterotrophic processes (Sadro and Melack 2012). Though rivers have higher particulate matter turnover that may dampen these effects when large rainstorms occur, the metabolism changes in response to the types of organic matter present are much the same.

Large flow events flush sediment as well as carbon particulates into streams. High peaks in turbidity occur when high flows scour the bed and banks of streams and drought-dried soils provide ample supply for sedimentation. In forested headwater streams, in-channel erosion of banks and the streambed have been found to contribute more to sediment load than inputs from hillslope during average precipitation years (Martin et al. 2014). In drought years, lowered groundwater levels may result in increased streambed erosion as the channel incises toward the water table. During large rainstorm or snowmelt events, high peaks in turbidity in the river occur, often correlated with the first high flow event in a season rather than the largest flow event (Martin et al. 2014, Mazurkiewicz 2011). Peak turbidity events have been shown to be highest in snowmelt pulses and slightly less in autumn, when sediment is flushed out after the summer period of low flow (Martin et al. 2014). Following a drought, large rainstorms bring high spikes of turbidity and raise levels of DOC.

**Water Delivery From Hetch Hetchy**

Large flow events, particularly during or after drought, can rapidly change water quality to below standards for drinking. By EPA standards, water with greater than 5 Nephalometric Turbidity Units [NTU] is not acceptable for drinking, and filtered supplies must maintain less than 1 NTU for two consecutive months (Oram 2014). A flow event in 2010 in the Tuolumne River was recorded to have peak turbidity levels of 120 NTU in the Tuolumne Grand Canyon and over 10 NTU in the Hetch Hetchy reservoir, much higher than EPA standards. Turbidity in the reservoir dropped back down to safe release levels in about 7 days, though the water needed to be filtered for 10 days after the initial peak in the reservoir (Mazurkiewicz 2011). During and after high flow events, particularly after drought, SFPUC must filter its water before supplying it to residents; this is a small price to pay for obtaining clean water the rest of the year from the river.

Interactions of chemical toxins may also be present in the water and affect drinking water quality. Changes in stream conditions have been shown to lead to increases in toxic bacteria that are more tolerant of higher temperatures (Wright et al. 2014). Some municipal water supply is treated with various disinfectants to improve taste and odor. However, microbial disinfectant treatments can interact with organic matter, forming byproducts [DBP's] that are harmful to humans (Nguyen et al. 2002, Wright et al. 2014). SFPUC avoids these risks by treating Hetch-Hetchy's water with UV light to clean it. The light kills all microbial life and avoids the risk of using disinfectants. Even in post-drought resurgence of flows high in POM and DOC, the water SFPUC diverts at Hetch Hetchy is safe for drinking.

The responses of the Upper Tuolumne River to periods of drought include altered vegetation, animal and invertebrate abundances, decreased carbon flux, and changes in the sediment transport conditions. These changes to the biotic and abiotic processes during drought increase water temperatures and lower dissolved oxygen content, degrading the health of the aquatic ecosystems. After drought, large precipitation events refill streams with water carrying high loads of coarse particulate matter and sediments, causing short-term disturbances to in-stream communities. For humans, even during the worst drought conditions in the watershed, Hetch Hetchy Reservoir is not particularly at risk for drought-related water quality impacts because of its exceptionally pure water conditions.

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