Sally Keating
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A Shifting Precipitation Pattern and Its Implications for the Tuolumne Watershed

Introduction

The plants, animals, and human infrastructure of California are adapted to a seasonally different system. While winter storms release brief pulses of floodwater, the majority of precipitation falls as snow, and remains at high elevations for the majority of the year. Although little to no precipitation occurs in the warmer months, in the past the species that call this region home have been able to rely on the slow release of alpine snowmelt for water. The annual cycle of wet and dry, and low flow regimes in regions such as the Tuolumne River Watershed allow the local geomorphology to exist in dynamic equilibrium: although extreme floods may significantly alter basin hydrology, the system has time to reset and slowly return to the lowest energy state available. Despite the dynamic nature of the natural flow regime, changes in precipitation patterns due to anthropogenic climate change could throw off the delicate balance and significantly alter the morphology and sediment supply of the river.

Changing Climate

As anthropogenic climate change progresses, the current hydrologic system is compromised because mid-elevation regions of the Sierra are highly vulnerable to rising temperatures. From 1880 to 2012, average annual global temperatures have increased by a range of 0.65 to 1.05 degrees Celsius (IPCC 2014). Mid-latitude regions such as the Sierra experience near-freezing temperatures through early spring from 5000 to 8000 feet (Reich et al 2018). In the current system, snow rests at elevations as low as 8000 feet until early April (Mount et al 2010). Under a “business as usual” greenhouse gas emissions model, spring temperatures in the mid-altitude regions of the Sierra Nevada are projected to increase by 7°C by the end of the century (Reich et al 2018). Temperature increase is exacerbated at these altitudes due to the loss of snow albedo feedback (Schwartz et al 2017). As temperatures rise just above freezing, snowmelt initiates earlier and the snowfield boundaries recede. Loss of snow cover results in a loss of reflective surface, such that the exposed ground absorbs solar energy rather than reflecting it, which promotes further warming of the region in a positive feedback cycle. As temperature increases earlier, less precipitation will fall as rain. For cold storms near 0 °C, temperature increases as small as 0.4 °C can cause precipitation to shift from snow to rain (Willis et al 2011). When precipitation falls as rain, runoff occurs much sooner. Under the “business as usual scenario”, the date by which 50% of the annual cumulative surface runoff has occurred will arrive up to 80 days sooner; even with significant environmental mitigation, the date will arrive at least 40 days sooner (Schwartz et al 2017). As melt water pulse timing migrates to earlier in the year, most of the water will have passed through the system during cool wet months. By the time summer arrives, if the majority of melt water is already gone, there won’t be as much available during the most arid time of the year.

Winter Floods in the Tuolumne

The loss of snowpack in the Sierra Nevada will promote increases in discharge during the winter and attendant decreases in stream levels during the summer. In order to understand how these changes will affect the sediment distribution of the Tuolumne River Watershed, it is essential to first examine where the majority of the sediment is produced. The majority of the sediment that passes through the Tuolumne River

Watershed system originates in the uppermost region called the source zone. The source zone spans from 4000 to 13000 feet in elevation, and is primarily composed of granitic bedrock overlain by a thin veneer of soil (Mount et al 2010). Tuolumne Meadows is located at 8000 feet, and is the product of sediment filling a cirque. Below Tuolumne Meadows, the river enters the Grand Canyon of the Tuolumne River, which is a narrow bedrock channel.

Despite an increase in the quantity of overland flow, the granitic bedrock of the Sierra is unlikely to experience a significant increase weathering. Studies examining climatic control on erosion find little, if any, increase in weathering with an increase in temperature and precipitation. This is likely due to a lack of freshly exposed rock surfaces for chemical weathering to occur and the overall resistance of the bedrock to erosion (Riebe et al 2001). While some sites had weak trends correlating erosion and temperature increase, these rates appear insignificant next to the erosional power of the glaciers that dominated the landscape in the past (Riebe et al 2001). Overland flow additionally shows little impact on soil production (Dixon et al 2009). The changing flow regime is therefore unlikely to add new soil and sediment available for transport. It may, however, have the ability to redistribute the sediment that is already present.

Changes in the intensity and timing of precipitation in the Sierra may drive changes in seasonal sediment budgets. While the majority of the source zone is bedrock with little to no soil cover, Tuolumne Meadows has a thick layer of soil and relatively sparse vegetation. The gradient is very low, and the river meanders quite a lot (Mount et al 2010). An analogous alpine meadow in the Kings River Watershed (just south of Tuolumne) had approximately 12% silt within its stream sediment, higher than most alpine streams (Hunsaker and Neary 2012). While the silt may be able to remain within the stream during average flow conditions, more will be mobilized during rain-induced overland flow. At high elevations, the primary surface sediment erosion and transport mechanism is overland flow (Dixon et al 2009). A seven year study of eight watersheds within the Kings River Watershed system demonstrated that stream sediment load differs significantly on an annual basis, and is primarily a function of the amount and intensity of precipitation (Hunsaker and Neary 2012). As overland flow intensity and frequency increases during the winter (when precipitation formerly fell as snow), there will likely be more suspended sediment load within the river and channel erosion within the meadows.

As discharge concentrates over a shorter interval, the soil saturation buffer becomes less effective at retaining water. In the past, winter floods have occurred on an annual basis, but were isolated and pronounced peaks on the system's hydrograph (Mount et al 2010). During these floods, alluvium and soils absorbed and retained overland flow and acted as a system buffer, reducing the amount of discharge until the ground was saturated and could no longer hold water. Because the floods generally had dry periods between them at low elevations, the water absorbed by the soil and sediment slowly released back into the stream. Now, however, as precipitation falls more readily as rain, overland flow and flooding occurs more frequently (IPCC 2014). The periods between floods are subsequently shorter, and the soils remain saturated. Water from a following flood will therefore remain as discharge, and increase overall short-term storm runoff. Studies of a California basin experiencing near-freezing storms demonstrated that 0.4 ^{o}C, 1 ^{o}C, and 1.4 ^{o}C temperature increases corresponded to 9.7%, 22.2%, and 30.8% increases in discharge volume, respectively (Willis et al 2011). Although an increase in overland flow has little effect on the erosion of resistant granitic boulders in the source zone, it can severely damage and change the sediment and soil slopes below.

Soils are able to remain on slopes and hillsides because the effective normal stress fighting mobility is greater than the downward force exerted by gravity. When soil is saturated, however, pore water pressure counteracts the effective normal stress, making the slope less stable and increasing the slope's vulnerability to landslides (Crozier 1986). Landslides introduce a high flux of sediment into the river, which can alter the channel morphology by eroding stream banks and redistributing sediment.

Dry Summers and Wildfire

Despite more severe precipitation intensity in the winter, the Tuolumne River Watershed is predicted to encounter hotter and drier summers. Although precipitation volume is unlikely to change drastically in this region of California (Pavelsky et al 2012), it remains concentrated almost entirely in the winter. In the past, the dry season was aided by the discharge of snowmelt from April until the end of June (Mount et al 2010). But as more precipitation falls as rain during the winter, the snowpack accumulates less volume and depletes earlier.

A transition to drier conditions imposes a threat of wildfire increase. Studies of the southwestern United States determined that 56% of wildfires and 72% of burned areas occurred in years with early snowmelt (Westerling et al 2006). Wildfires have several influences over the morphology of a watershed, the most obvious being vegetative cover. Vegetation plays an important role in slope and channel stability of soil. Grasses and trees help keep soils in place by holding them with their roots. Riverbanks with grasses additionally demonstrate a higher resistance to erosion than those without

(Zonge et al 1995). When wildfires devastate the natural environment, they destroy the majority of the vegetation and therefore remove a stabilizing force from the soils. The soils themselves are additionally altered. Although the degree of weathering and alteration depends on the soil composition and the temperature the soil reaches, most studies have found that wildfire makes soil more friable, less cohesive, and more erodible (Shakesby and Doerr 2015). The increased erdodibility of affected slopes implies an increase in sediment supply to nearby streams, as gravity and precipitation drive loose particles down hill. An increase in sediment supply during the summer, when discharge is low (Mount 2010), can apply a number of geomorphic changes to a channel by means of deposition, including bed aggradation, channel narrowing, and increase in channel sinuosity (Dean et al 2016).

Conclusion

Even with only minute changes in annual temperatures, anthropogenic climate change will greatly impact the hydrology and geomorphology, and therefore ecology, of the Tuolumne River Watershed. Winter storms that occur near freezing will occur as rain rather than snow, fundamentally altering the distribution and timing of stream flow through the watershed. More rainfall in the winter implies more overland flow, which can potentially redistribute existing sediment from the source zone and generate more through landslides and debris flows in the middle and lower regions. As spring snowmelt shifts to earlier in the year, the Sierra Nevada landscape is left little recharge for longer periods of time. Intensified summer drought periods will promote a higher risk for wildfires, which increase the erodibility of soils. These changes imply severe impacts on the riparian ecology that has adapted to rely on the current hydrologic and geomorphic system. In order to determine the extent to which these environments change, further work should examine the distribution and abundance of sediment within the Tuolumne basin.

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