Integrated Vulnerability Assessment of Climate Change in the Lake Tahoe Basin

Technical Memos

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Lake Tahoe Vulnerability Assessment

Date: March 29, 2019

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RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Lake Tahoe

Resource Profile – Summary of Historical, Current, and Future Climate Conditions

Long term data through 2017 indicate that Lake Tahoe has experienced its greatest warming in recent years with the highest rates at the surface of the Lake. In 2017 the peak surface temperature was 4^0C warmer than the previous 3 years. The rate of surface temperature warming between 1968 and 2017 was 0.02^0C/yr. This has caused increased resistance to mixing and an increased stratification season that increased by 24 days from 1968 to 2014.

Some future climate scenarios forecast a trend for decreased lake mixing caused by increased stratification, and the occurrence of hypoxia leading to significant internal nutrient release. The stratification season may further increase by 62 days by the year 2098 (Sahoo et al. 2016). Increased stratification has been shown to favor the growth of smaller phytoplankton and thus reduce lake clarity.

Resource Sensitivity and Exposure to Climate Change

Lake Tahoe has already shown itself to be sensitive to climate change, with significant increases in its temperature and internal physics (e.g., frequency of deep mixing, onset and breakdown of thermal stratification, interaction with inflowing streams). The climate-change-induced air temperatures experienced to date are far lower than those expected in the next 50-100 years, so disproportionality larger effects are expected for the Lake. As a system dependent on the health and function of other systems (i.e., watershed runoff, forest health), Lake Tahoe has little-to-no ability to adapt to changes. On the contrary, to the extent that the Lake exerts a cooling influence on the region, the buffering effect of the Lake on the local ambient air temperatures may decrease in the future. As lake temperatures rise at all depths and in all seasons, organisms that are approaching the upper limits of their thermal ranges may experience increasing stress. For example, Lahontan cutthroat trout begin to show signs of acute stress at temperatures >22°C; (Dunhamet et al. 2003). Similarly, organisms better suited to warmer waters may find Lake Tahoe increasingly hospitable. Warmwater non-native fishes like Bluegill and bass may be able to establish further, impacting native fish biodiversity (Chandra 2009).

Impacts and Implications of Climate Change

Climate change has impacted and will continue to impact Lake Tahoe. Water temperatures will continue to increase from previously recorded temperatures. More importantly, lake warming will not be uniform over its depth, resulting in an increase in the thermal stratification, which will retard the mixing needed for healthy lake function. Warmer temperatures along with longer droughts and increased evaporation may cause Lake Tahoe to go below the natural rim, affecting water supply to downstream communities. The range of consequences of this are large, including:

- Inflows of stream water and urban stormwater may get trapped closer to the surface, reducing clarity and adding nutrients to the euphotic zone (including the littoral areas).
- Reduced UV penetration may increase pathogen viability and allow for the reproduction by non-native species.
- Different species of phytoplankton may dominate the lake flora, continuing the trend that has already been observed.
- The expected reduction in frequency and duration of deep mixing may not replenish dissolved oxygen in the deeper parts of the Lake, producing areas of hypoxia (dead zones) that will release large fluxes of internal nutrients.

Key Elements of Adaptive Capacity and Resilience

A few options appear capable of slowing warming and increased stratification of the Lake, and more importantly, keeping key elements of the ecosystem intact. An improvement in lake clarity, a central goal of the Environmental Improvement Program, would partially offset some of the warming effect and directly reduce the rate of surface temperature increase. Recent data show that the removal of the introduced Mysis shrimp and the re-establishment of native fauna (e.g., daphnia) may help improve lake clarity. Reducing biomass production, by further reducing nutrient fluxes into the Lake, could reduce the Lake’s oxygen demand and avert hypoxic conditions.

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Aquatic Resources Vulnerability Assessment

Date: March 29, 2019

By: Sudeep Chandra, PhD, University of Nevada, Reno

RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Aquatic Resources

Resource Profile – Summary of Historical, Current, and Future Climate Conditions

There have been either extirpations of species (e.g. cutthroat trout) or declines of native forage fishes over decadal periods of time. Native Lahontan cutthroat trout have been extirpated in the Basin since the late 1930s; this likely occurred due to the hybridization with introduced nonnative rainbow trout, predation by introduced lake trout, and poor water quality in streams and rivers due to changes in land-use practices. There have been a number of attempts to "reintroduce" or maintain cutthroat trout populations through stocking into Fallen Leaf Lake or management of nonnative brook trout in Meiss Meadows in the Upper Truckee River Basin. While efforts to introduce Lahontan cutthroat trout in the main body of the Lake have not occurred, successful reintroduction will require a number of items including access streams to produce viable populations within the Lake.

Previous studies conducted by Cordone (unpublished data 1960) and Thiede (1997) showed that native forage fish densities have experienced sharp declines of nearly 10-fold between the 1960s and late 1990s. More recent, snapshot studies indicate a continued decline of all native fishes with some fishes absent from specific sites or a 30% reduction in spawning activity from measurements a decade prior. Reasons for the declines in native fish densities have been attributed to predation by invasive warmwater fishes and signal crayfish, predation by introduced lake trout (*Salvelinus namaycush*), or changes to condition of nearshore habitat (Vander Zanden et al., 2003; Chandra et al., 2009; Kamerath et al., 2008; Ngai et al., 2013). Nearshore habitat changes may be due to fluctuating lake conditions which may dry out active nests or reduce habitat during drought versus wet years. Continuous monitoring of fish populations is needed to understand how fluctuating lake levels influence longer-term dynamics.

A snapshot study between a 40 year period, 1960s to 2000s, indicate dramatic alterations to benthic invertebrate densities and community structure. For example, Lake Tahoe's midge assemblage is now more taxon rich today. The midge assemblage has shifted from few genera, of which nearly 25% indicated oligotrophic conditions, to many genera, of which only, 10% indicate oligotrophic conditions according to trophic ranges developed for midge taxa by Saether (1979). The assemblage of midges collected during our 2008–2009 survey was composed of more cosmopolitan genera, such as *Tanypus* and *Chironomus* (Cranston et al. 1989, Murray and Fittkau 1989); more warm-adapted genera, such as *Clinotanypus* (Murray and Fittkau 1989); and more pollution-tolerant taxa, such as *Cricotopus bicinctus* (Huggins and Moffett 1988), when compared to chironomid taxa collected in 1962–1963. Despite small differences in worm densities between 1962-1963 and 2008-2009, the assemblage structure of worms in Lake Tahoe appears to have changed. At least 7 invertebrate species that were collected in 1962-1963 were not encountered or found in 2008-2009. The two endemic blind amphipods (*S. lacicolus and S. tahoensis*) declined 99.9% in lakewide density since 1962–1963. Two endemic turbellarians were abundant and widespread in samples in the 1960s, but no endemic turbellarians were collected in 2008– 2009. The lakewide density of the endemic Tahoe stonefly decreased 93.5% since 1962-1963. Although still widespread in Lake Tahoe, the lakewide density of endemic ostracods decreased 83.4% since 1962-1963.

Native zooplankton have changed community structure over time and some have exhibit some resilience since the 1960s. With the introduction of invasive mysid shrimp in the 1960s, there has been a near elimination of the filter feeding cladoceran community from the main part of the Lake although populations do occur in the nearshore and embayments. Populations of native *Bosmina* have been observed in the main lake when there is sufficient phytoplankton for growth (Byron et al., Chandra 2005). Two native copepod species still occur in the Lake and have not decreased in numbers. Zooplankton growth, in general, is closely linked to temperature and food supply, with population dynamics determined also by predation.

There is little information on the historical changes of native plant structure or densities. Deepwater plants like macro algal *Chara* spp., which are important for supporting native benthic invertebrates and sport fishes likely existed much deeper (mainly from 45 to 90 m) than they are found today (Frantz and Cordone 1967), presumably due to greater clarity and light availability at the bottom of the Lake in the

1960s. Direct influences of temperature are not clear although indirect influences of temperature may occur by increasing populations of predators.

Resource Sensitivity and Exposure to Climate Change

Lake Tahoe's native biodiversity may be particularly sensitive to climate change given their already reduced numbers and reduction in their habitat. For example, coldwater native cutthroat trout can reside in the deeper lake waters but require access to streams for spawning. The timing of discharge in streams, maintenance of cooler waters through slow release of water into the streams over the spring to early summer periods, and persistence of water is needed to recruit fishes into the population. Warmer winters or warm after cold precipitation conditions could result in the lack of connectivity between the Lake and stream for cutthroat populations.

Fluctuating lake levels due to extended droughts and/or periods of rapid increases in lake level due to increased precipitation events will impact available habitat for native forage fish spawning and rearing. The optimal habitat in the nearshore environment is already limited in the Lake for these activities. In addition to the possibility of increasing suboptimal habitats for native fish rearing, native fishes may be negatively influenced through competition with and predation by invasive warmwater fishes. Ngai et al. (2009) suggested that certain parts of the nearshore environment will warm in the future. Invasive warmwater fishes may expand from their current occupied areas in the nearshore (e.g., Tahoe Keys) and recruit as temperatures in the nearshore warm or growing seasons are extended in the summer. Invasive warmwater bluegill compete with native fishes, and warmwater bass are predators for native fishes, reducing their densities (Kamerath et al. 2008).

Climate change may alter the native and nonnative balance of benthic invertebrate diversity in the Lake. Wittmann et al. (2013) found that longer growing seasons can yield higher densities of invasive clam populations by increasing their reproductive output. Clams filter feed water and can alter nearshore algal communities and diversity (Wittman et al., Denton et al.), changing the habitat for native invertebrate taxa. In addition, elevated temperatures are thought to be increasing the densities and expansion of coldwater crayfish at Crater Lake (Oregon), an ultraoligotrophic ecosystem similar to Lake Tahoe. Thus, alterations to the temperature or expansion of the growing season may support increased densities of invasive crayfish which feed on benthic invertebrates, macroalgae and native fish eggs.

Impacts and Implications of Climate Change

As lake conditions change, climate change will alter aspects of the Lake's native biodiversity. Alterations to the native biodiversity will impact how nutrients and particles delivered from the watershed are processed. For example, with a reduction or elimination of benthic taxa, there could be substantial changes in how and when the particles that settle to the lake bottom are processed. When the Lake mixes, particles are reintroduced to the water column and excess particles and organic matter that were not processed by benthic invertebrates or zooplankton may result in the loss of clarity. Alterations to the fish community assemblages change the food available for nonnative sportfish. Finally, nutrients control algal dynamics in the Lake. Excretion of nutrients by animals and release by plants can be altered when there is a change in biological assemblage, changes to the migration and movement of species, or death.

Key Elements of Adaptive Capacity and Resilience

Key elements of adaptive capacity and resilience depend on the type of native biodiversity within Lake Tahoe. Currently very little research has occurred at Lake Tahoe to link fundamental processes to lake biodiversity, production, and function. However, some key elements for native taxa are as follows:

- Reduce the vulnerability of native biodiversity by expand habitats and range for native cutthroat trout; expand habitat by increasing structures (e.g., cobbles and gravels) for native fishes; and restoring the deep-water bottom of Lake Tahoe for endemic species
- Adaptive management of communities and their populations utilizing population dynamics and community interaction information
- Initiate conservation planning for vulnerable communities (e.g., endemic deepwater plants and invertebrates) that includes strategies that a) eliminate disturbances (e.g., biological invasions or removal of species) that are not climate related; b) have explicit ex-situ strategies and resources provided so taxa do not go extinct; and c) incorporate population- and community level genome to ecosystem function relationships.

Watershed Hydrology & Streamflow Vulnerability Assessment

Date: March 29, 2019

By: Alan Heyvaert, PhD, Desert Research Institute

RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Watershed Hydrology

Resource Profile – Summary of Historical, Current, and Future Climate Conditions

Mountain hydrology is very sensitive to slight changes in climate, particularly temperature and precipitation. As a result, streamflow in the Tahoe Basin is expected to change with climate, both in terms of water quality and in terms of runoff volumes. Historically, the average annual unit runoff values (volume/drainage area) for water years 1988–1998 as calculated by Rowe et al. (2002) on ten representative streams in the Tahoe Basin ranged from 163 acre-ft/mi2 at Logan House Creek near Glenbrook to 2,280 acre-ft/mi2 at Blackwood Creek near Tahoe City (Figure 1). The highest daily mean streamflow (3,150 ft3/s) and the highest instantaneous streamflow (5,480 ft3/s) were both measured in the Upper Truckee River at South Lake Tahoe during a rain-on-snow event on January 2, 1997. This New Year's flood of 1997 was considered the largest runoff event in 90 years of record for northern California. Preliminary projections of extreme runoff events evaluated for selected streams around Lake Tahoe showed significantly increased maximum daily discharge (MDQ) for most streams under climate change predictions from RCP 8.5 (Lewis 2019 personal comm.), with MDQ in the Upper Truckee River, for example, increasing by about 60% at the 20-year return frequency level (Figure 2).

The annual precipitation totals are not expected to change markedly, perhaps by ±10–15%, but the timing and type of precipitation (rain vs. snow) will shift toward larger storms with rain occurring earlier in the year, along with rapid reversals between extended drought periods and extreme wet years (Dettinger et al. 2018). Climate change in the Tahoe Basin will bring more extreme conditions overall, with increasing intensity of storms, more rain-on-snow events and floods, and more extended droughts.

With warmer temperatures to come, the bulk of annual runoff will shift toward earlier seasonal snowmelt and rainfall. This seasonal redistribution of the annual streamflow will increase winter and early-spring runoff while decreasing the summer runoff rates (Figure 3). With reduced or minimal summer snowpack, both soil moisture and groundwater recharge are projected to decline along with overall-drying impacts on vegetation.

Runoff water quality responds to storm intensity, timing and volumes, and will likely respond to increased temperatures as well. The stream water temperatures during periods of record up to 1998 ranged from 0°C at several gaging stations during winter months to a maximum of 23°C at two lower elevation stations during the summer months. With daily minimum and maximum temperatures expected to rise by 2–3°C under RCP 4.5 and by 5°C or more under RCP 8.5, we can expect increasing stream water temperatures as well, which will affect aquatic life and fish spawning habitat. Earlier snowmelt runoff will lead to reduced baseflow later in the year, resulting in more intermittent or ephemeral stream conditions and warmer water during these times. In contrast, periods of deluge runoff will cause more scouring and erosion from the landscape, potentially increasing nutrient and sediment concentrations and loading. The biogeochemical processes associated with nutrient cycling in streams and across the landscape are complex and interacting, with net effects from changing climate largely unknown but likely to be relevant to lake loading rates, aquatic species diversity and terrestrial vegetation structure.

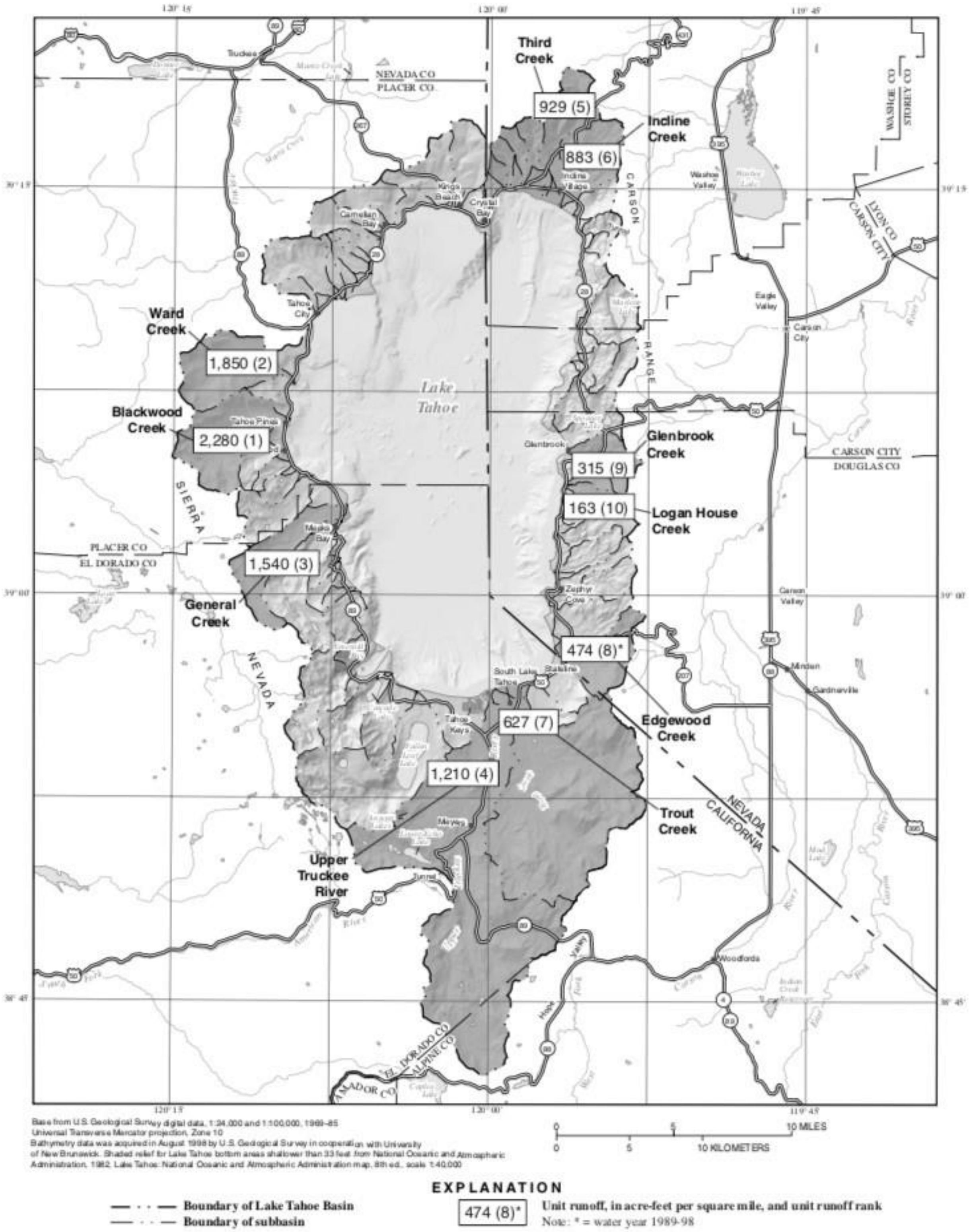

Figure 1. Unit runoff and unit-runoff rank for 10 primary LTIMP stations for water years 1988–1998 (from Rowe et al. 2002).

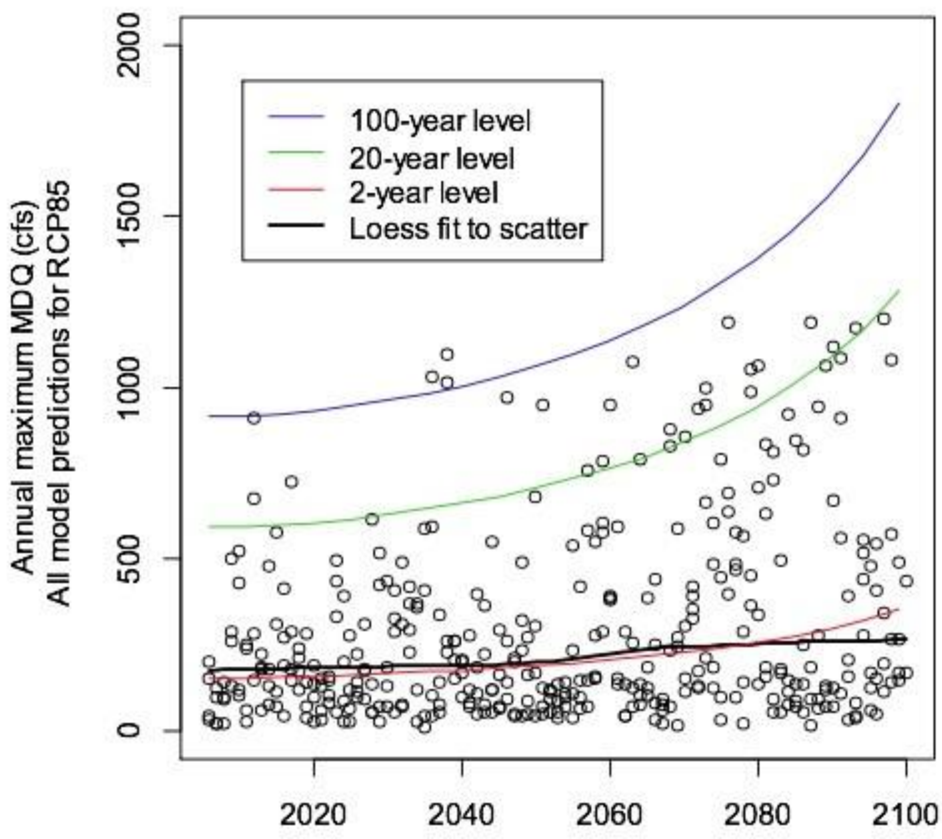

Figure2. GCM models predict annual Maximum Daily Discharge (MDQ) increases in the Upper Truckee River by about 60% at the 20-year return frequency level (J. Lewis, 2019).

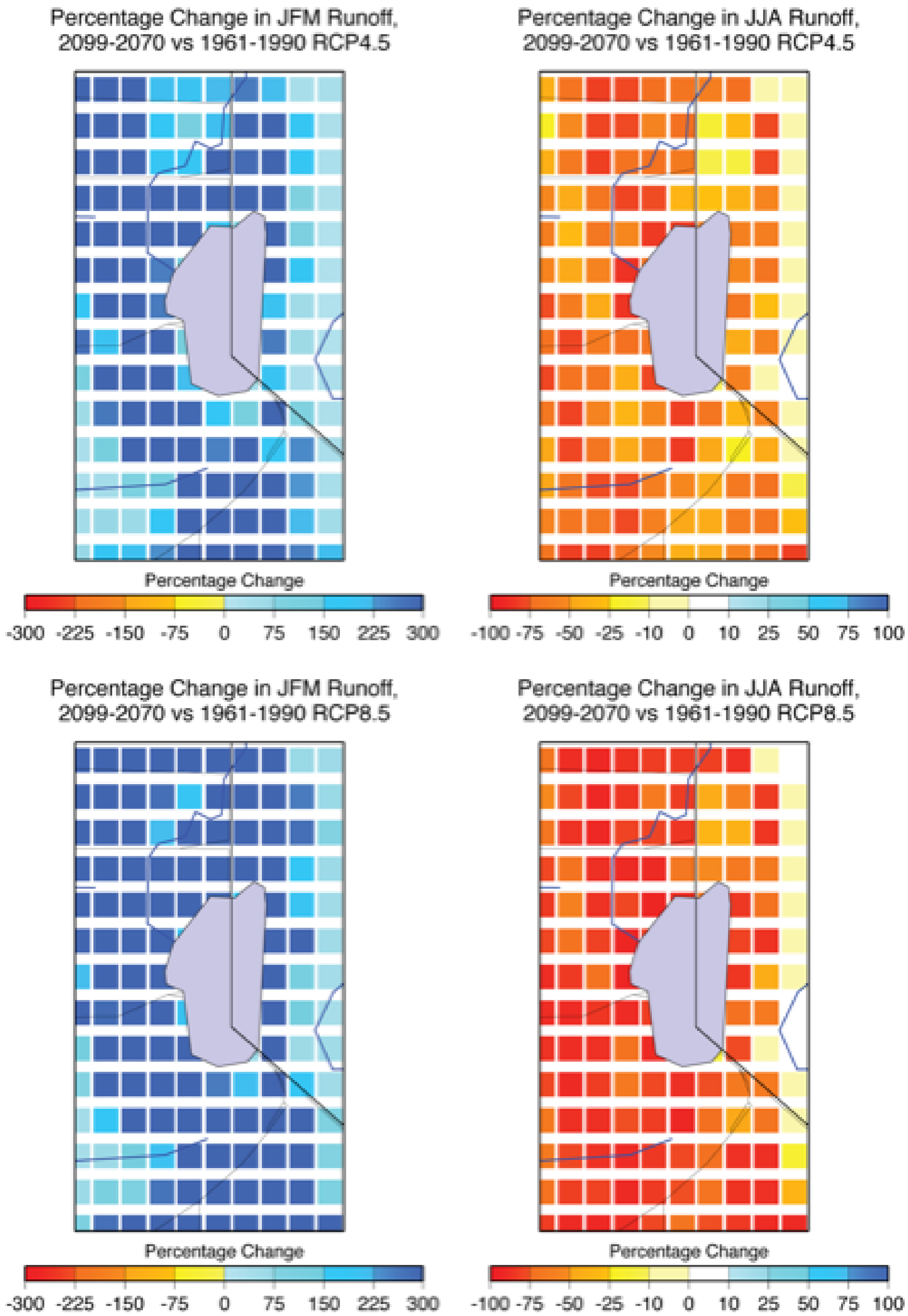

Figure 3. Percentage change in January-February-March (JFM) runoff volumes and June-July-August (JJA) runoff volumes around the Tahoe Basins under RCP 4.5 and 8.5 (extracted from Dettinger et al. 2018).

Resource Sensitivity and Exposure to Climate Change

Mountain hydrology is highly sensitive to slight changes in climate, particularly temperature and precipitation. Temperatures in the Basin are projected to warm 6°F to 9°F on average and the precipitation changes may be ±10-15% of current totals. These forecasted conditions lead to naturally high variability in seasonal and interannual patterns of snowpack accumulation, which in turn affects watershed storage and runoff, which then affects local ecological conditions and downstream water resources. Climate change is expected to exacerbate this inherent variability and may ultimately shift hydrologic patterns across thresholds that would result in long-term changes to both biological structure and function as well as the resource assets of surrounding communities.

Given both the 4.5 and 8.5 RCP projections, stream water temperatures will trend upward with climate change, causing shifts in aquatic species and in-stream nutrient cycling. Dissolved oxygen concentrations decreases with increasing temperatures, so this may affect some species in riparian environments. Trends in nutrient concentrations and loading are more difficult to predict, given complex biogeochemical cycling processes, but it is likely that both nitrogen and phosphorus will increase due to more growth of nitrogen-fixing blue-green algae and due to increased phosphorus mobilization from erosion as more rainfall events occur on exposed soils that do not remain snow covered.

Anticipating the potential impacts from these changes will provide an opportunity to investigate resource management, ecosystem services and land use practices that would help mitigate the consequences of climate change. One example of this could be how often does Lake Tahoe go below the natural rim? Historically, especially during extended droughts, Lake Tahoe stage has gone below the rim for extended periods, which significantly reduces the supply from the Lake to the Truckee River, which causes curtailment of water downstream. The reservoirs downstream of Lake Tahoe, and how they are operated, are highly sensitive to the state of Lake Tahoe: hence, understanding how climate change may change the water budget of Lake Tahoe is extremely crucial to water security.

Impacts and Implications of Climate Change

With more of the total annual precipitation arriving as rain rather than snow, there will be a reduction in water storage of mountain snowpack and reduced streamflows later in the year, which will affect baseflow dependent ecosystems and other riparian areas.

Furthermore, these changes in snowpack are altitude dependent, so impacts will be spatially dissimilar, with quicker warming trends and precipitation changes at higher elevations (Dettinger et al. 2018).

More extreme hydrologic events are predicted, with increasing intensity of storms, rain on snow events and floods. The precipitation from larger storms will be increasing by 5–30%, leading to higher flow runoff events and corresponding impacts on erosion, pollutant transport and damage to infrastructure, which will require design specification review and modification by highway engineers and floodplain managers.

Changes in precipitation and hydrology will not be uniform across the Tahoe Basin, due to its complex terrain and rain shadowing effects. Orographic rain shadowing typically reduces precipitation eastward from the crest of the Sierra Nevada, so drought impacts are likely to be exacerbated on the east side of the basin.

Trends in snowmelt timing and peak flows shifting to winter and early spring could have significant consequences to downstream water supply (Barnett et al., 2005; Barnett et al., 2008). Warmer temperatures, along with longer droughts and increased evaporation, may cause Lake Tahoe to go below its natural rim and affect water supply for longer periods to downstream communities.

More intense storms and more rain-on-snow events will challenge existing stormwater infrastructure, their hydraulic capacity and treatment effectiveness. Water quality inputs to Lake Tahoe would deteriorate as a result.

Key Elements of Adaptive Capacity and Resilience

Anticipating the potential impacts from these changes will provide an opportunity to investigate resource management, ecosystem services and land use practices that would help mitigate the consequences of climate change.

- Winter precipitation in the Tahoe Basin is due to moisture that spills over from the westerly orographic uplift. As the proportion of rain vs. snow increases due to warming, the amount of moisture that spills over to the east of the Sierra Nevada may diminish (Pavelsky et al. 2012). Understanding spillover precipitation and its change in the future has significant consequences for predicting hydrology and water supply to Lake Tahoe and downstream communities.

- With a smaller proportion of winter precipitation falling as snow due to increased surface warming, the occurrence of rain-on-snow flooding may increase. Methods to forecast such events and building flood resiliency in the system will need to be improved
- Stormwater infrastructure for conveyance and treatment will need to be designed to accommodate larger and more frequent runoff events. These will also need to be maintained to standards that achieve much better water quality, suitable for discharge to Lake Tahoe, than is typical of stormwater best management practices in other parts of the country.
- Warmer temperatures along with longer droughts and increased evaporation may cause Lake Tahoe to go below its natural rim more often, affecting water supply to downstream communities. The Lake's reservoir capacity may need to be managed more actively and dynamically to simultaneously enhance water supply and mitigate downstream flooding.

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High-Elevation Groundwater Vulnerability Assessment

Date: March 29, 2019

By: Alan Heyvaert, PhD, Desert Research Institute

RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of High-Elevation Groundwater

Resource Profile – Summary of Historical, Current, and Future Climate Conditions

There is limited information on recharge processes and groundwater characteristics of higher elevation groundwater systems in the Tahoe Basin and the Sierra Nevada. Conditions vary markedly over short spatial and topographical scales in these mountain environments. Aquifers can be smaller, disconnected and sensitive to slight changes in precipitation and temperature. It is not known how climate will affect fractured bedrock aquifers, high mountain springs, mountain meadows and headwater streams at the higher elevations (Dettinger et al. 2018). The highest elevation groundwater dependent ecosystems, those above 9000 feet, may be more resilient as snowpack will persist longer at these elevations, but the mid-elevation systems will likely suffer from reduced snowpack, more frequent runoff and erosion, and dropping groundwater levels.

High elevation wetland environments around springs, seeps and wet meadows are sustained by high soil moisture content from persistent subterranean groundwater sources that are augmented by snowpack and snowmelt, especially where slope gradients are low (Rundel and Millar 2016). These are very climate sensitive ecosystems dependent on seasonally or perennially saturated soils from the slow release of snowmelt. Climate change can cause groundwater levels to drop, which would isolate these systems from their defining resource and cause basic changes in vegetation and associated species.

Resource Sensitivity and Exposure to Climate Change

Dettinger et al. (2018) noted that groundwater systems can buffer the impacts of long- and short-term droughts, although the relatively smaller and often isolated aquifers in mountainous parts of the Sierra Nevada region are particularly vulnerable to changes in recharge and snowmelt. Since changes in snowpack are altitude dependent, these impacts will be spatially dissimilar across the landscape.

One study on the impacts of increasing temperatures on stream connected groundwater systems at Lake Tahoe looked at historic data and GSFlow model simulations for Third, Incline, and Galena Creeks (Huntington and Niswonger 2012). They demonstrated indirect and interacting affects between the surface water and groundwater, with groundwater discharge to the streams inversely correlated to snowmelt runoff and groundwater recharge where groundwater flows into the streams peaked after the seasonal decrease in stream depth with snowmelt recession. Their models showed that this was due to a bank storage effect and the reversal of hydraulic gradients between streams and groundwater when stream levels dropped. The overall result was enhanced depletion of groundwater, with more than a 30% decrease in summertime flows when averaged across all GCM projections of increasing temperatures. They concluded that snow-dominated watersheds would become more arid during the hottest part of the year, and dry season water stresses would likely become more severe even if annual precipitation increased.

Impacts and Implications of Climate Change

More extreme hydrologic events are expected as the climate evolves, with an increasing frequency and intensity of storms like the atmospheric rivers that produce heavy rain and rain-on-snow events. With more intense rainfall events over shorter periods during the year, the total infiltration to groundwater storage will decrease compared to the same amount of annual precipitation spread over smaller events through the year.

Groundwater storage in small higher elevation aquifers can respond quickly to changes in snowfields and local recharge rates and timing (Dettinger et al. 2018). Since precipitation magnitude is the dominant condition controlling groundwater recharge, and since precipitation in the Lake Tahoe region is not expected to change dramatically (±10–15%), one might assume that groundwater recharge would remain consistent with historical patterns. This may not be the case, however, due to longer growing seasons with increased and prolonged evapotranspiration demand, decreasing infiltration from more intense rain events, and discharge losses to summer streamflows. Lower groundwater levels under wetland areas will lead to forest encroachment and loss of habitat. These areas may become sentinels of climate change progression for mid-range elevations in the Tahoe Basin as the snowline rises with increasing temperatures.

Key Elements of Adaptive Capacity and Resilience

Meadow hydrology, wetland soils and wet meadow vegetation are interdependent, supported by shallow groundwater, so cascading changes are expected in these systems and their associated stream environment zones (SEZs) at Tahoe. Monitoring the condition of montane wetlands, springs, intermittent streams, and groundwater levels will provide early indication of climate change impacts to upper elevation environments. One strategy that would help sustain higher elevation groundwater resources is to maintain healthy forests and riparian areas that will slow the release of snowmelt and streamflow. Appropriate meadow restoration projects would prevent stream downcutting and water table depression, while also helping to build organic soils, disperse flood flows and increase groundwater storage (Hunt et al. 2018). Finally, the occurrence of invasive species should be identified and controlled before they become detrimental to wetlands and high elevation groundwater retention and storage.

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Low-Elevation Groundwater Vulnerability Assessment

Date: March 29, 2019

By: Alan Heyvaert, PhD, Desert Research Institute

RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Low-Elevation Groundwater

Resource Profile – Summary of Historical, Current, and Future Climate Conditions

Hydraulic conductivity, specific yield and aquifer thickness are properties that determine storage and movement of ground water. Most of the lower lying portions of the Tahoe Basin aquifers are located in thick basin-fill deposits composed of silt, sand, gravel, and boulders from adjacent highlands (Thodal 1997). These basin-fill deposits exceed 100 feet in most of the major drainages, and in South Lake Tahoe area they average about 350 feet. Groundwater withdrawals can drawdown the water table and change the movement of water into or out of connected streams, lakes and wetlands, which can result in either decreased rates of discharge from the aquifer to these surface-water features or in aquifer recharge from the connected surface-water features. Pumping that causes increased inflow from connected streams to an aquifer and decreased outflow from that aquifer is called "streamflow depletion" or "capture" (Barlow and Leake 2012). Capture maps indicate the steady-state conditions that will persist when recharge and pumping are held constant on average over the long-term.

Capture maps modeled for the Tahoe Valley South groundwater basin in South Lake Tahoe (Pohl et al. 2018) revealed two areas where the sources to replenish water withdrawal are different. North of the Lake Tahoe Airport (proximal to the Lake) most of the water withdrawal is from Lake Tahoe. South of the South Lake Tahoe Airport (proximal to upland areas) most of the water withdrawal is from streamflow. Therefore, “not to exceed” recommendations were provided to limit pumping rates south of the airport so that stream ecology would not be harmed by streamflow losses due to pumping. Notably, the current groundwater extraction rates and allocations for the District were well below this recommended threshold. The point is that similar low-elevation groundwater systems connected to the Lake are expected to be relatively resilient to changing climate, unless lake level drops precipitously, and the Tahoe Valley South Basin groundwater system is expected to remain in a sustainable condition over a full range of climate projections, including RCP 8.5 (Pohl et al. 2018).

Resource Sensitivity and Exposure to Climate Change

Most low elevation groundwater areas in the Tahoe Basin that are well connected to the Lake should be less sensitive to climate changes than the higher elevation areas; and given the volume of Lake Tahoe, it is unlikely that groundwater pumping will significantly impact lake levels. The contour at which lake connectivity is insufficient to maintain groundwater levels (0.5 proportional capture) varies with geology, elevation, depth of the aquifer and pumping rates.

In the Tahoe Valley South study a drought scenario was created by piecing together 2012-2015 and 1987-1994 droughts to create a 12-year drought sequence, with a 5°F temperature increase added to represent average mid- century (2060) temperature increase (Pohl et al. 2018). In this extreme climate test case there was a 32% drop in recharge compared to the historical baseline, but water levels only declined from 0–10 feet. Similar results would be expected for other low elevation groundwater systems connected to the Lake, although conditions will vary based on their specific geologic and topographic characteristics.

Impacts and Implications of Climate Change

Groundwater systems can buffer the impacts of droughts, but they are ultimately vulnerable to changes in recharge and to increased water extractions because of drought. Although many of the low elevation groundwater systems around the Lake may be resilient due to their connections with the Lake, there are still limits to extraction rates if the ecological benefits of groundwater buffering are to be sustained.

Stormwater infiltration is often advocated as a best management practice with multiple benefits resulting from reduced overland flows, groundwater recharge, and natural pollutant removal processes. However, urban runoff in the Tahoe Basin is recognized as the dominant cause of lake clarity loss (LRWQCB and NDEP 2010), so the injection of this water into low elevation groundwater systems under urban areas surrounding the Lake may create longer-term cumulative impacts that have not been adequately investigated. However, more intense rainfall over shorter periods during the year will reduce the amount of total infiltration to groundwater. With less infiltration the runoff from these events could more frequently exceed capacity of existing stormwater BMPs and infrastructure.

Key Elements of Adaptive Capacity and Resilience

Lower elevation groundwaters connected to the Lake are likely to be more naturally resilient to climate change effects, with less change in water levels. This will help buffer the requirements of overlying ecological systems that intercept groundwater at these depths and will provide recharge capacity for consumptive extraction. Pumping from deeper layers in the aquifer will result in relatively more water withdrawal from the Lake and less from streams (Pohl et al. 2018). It will be necessary, however, to evaluate the specifics of aquifer characteristics to establish the extent to which groundwater levels will change with extraction and the corresponding delineation of 0.5 proportional recharge areas (lake versus stream sources).

Injection storage of stormwater runoff into aquifers could help replenish groundwater demand requirements at lower elevations where stormwater conveyance infrastructure exists. The implications of this practice on groundwater quality would need to be further investigated, however, before it could be recommended as a viable, long-term, large-scale strategy for sustaining groundwater aquifers near the Lake.

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Soil Moisture & Infiltration Vulnerability Assessment

Date: March 29, 2019
By: Alan Heyvaert, PhD, Desert Research Institute
RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Soil Moisture and Infiltration

Resource Profile – Summary of Historical, Current, and Future Climate Conditions

There is very limited data available on current or historic soil moisture conditions for the Tahoe Basin. In general terms for the Sierra Nevada, upper-elevation soils tend to be acidic, well-drained, shallow to deep, and fine to moderately coarse-textured, with moister drainages and higher organic content on north-facing slopes that have denser forests and have burned less frequently. Compared to lower elevation montane forest soils, there is a significant reduction in soil development above 1,800 meters, with clay content often dropping to less than 15% (O'Green et al. 2007) and limited soil moisture storage. Soil moisture naturally varies with elevation and slope exposure (aspect), as well as with the time of year, especially from March through August when evapotranspiration is supported by soil moisture derived primarily from winter precipitation and snowmelt infiltration. Historically, greater spacing in mature forest stands likely reduced competition for soil moisture (Gray et al. 2005).

Changes in Sierra Nevada soil moisture conditions during the typical June to September dry season are expected to be more severe with increasing altitude up to about 8500 feet, largely reflecting changes in snowpack (see Figure 1), Dettinger et al. 2018). This will affect forest structure and health.

Resource Sensitivity and Exposure to Climate Change

Warming temperatures will reduce the depth and duration of montane snowpacks, lengthening and deepening the summer dry period and exacerbating soil water deficits during droughts. This will likely increase moisture stress for many forests (Safford, North et al. 2012, McDowell and Allen 2015). Further, with more intense rainfalls events occurring over shorter periods during the year there will be less total infiltration compared to the historical pattern of annual precipitation spread over more smaller events through the year.

Warming temperatures will also raise snowline altitudes significantly, with much more precipitation falling as rain at elevations from lake level (near 6200 feet) upward to about 9000 feet or more. April snow-water equivalents will be reduced by 60–100% below 8000 feet (see Figure 1). This will decrease the depth and duration of montane snowpacks over most of the Tahoe Basin, lengthening and deepening summer soil water deficits and yielding changes in vegetation type, density and distribution. Shifting snowlines could also reduce insulating snowpack and make forests more vulnerable to damage from increased soil frost

Climatic water deficits, representing exceedance of evapotranspiration (ET) demand relative to available soil moisture, will increase for most of the Tahoe Basin and will be particularly severe along the north and east sections of the Basin. We can expect dramatic changes in forest health and structure by the end of the century with more insect infestations, tree mortality and potential wildfires in these areas.

Impacts and Implications of Climate Change

As the timing of seasonal snowmelt shifts toward earlier in the spring, there will be less soil moisture later in the year, with consequential impacts on drought-sensitive vegetation and dependent species. During droughts the amount of precipitation as rain and snow decreases but rates of evaporation from soil and plant transpiration (ET) remain the same or increase with warmer and drier conditions (Bales et al., 2018). As a result, there are likely to be longer-term changes in forest composition and distribution, as well as increased fire frequency, especially at elevations or exposures where fuel moisture content becomes critical. The north and east sections of the Tahoe Basin will become particularly vulnerable.

In some cases, however, short-term ecosystem accommodation to drought has been observed in the Sierra Nevada with dieback and wildfire thinning of forested areas that reduces evapotranspiration demand and leaves more water available for soil moisture, stream runoff, recharge and baseflows through the year (Bales et al., 2018).

Key Elements of Adaptive Capacity and Resilience

Outside of changes in regional weather patterns that would produce more precipitation events in the summer, there is little that can be done to increase soil moisture during the critical summer months when evapotranspiration demands are highest.

Sustaining mature healthy forests is probably one of the best strategies, with active forest management practices that result in thinning and optimal spacing of mature trees to reduce soil moisture competition. Many of the existing Tahoe Basin forest stands are overly dense as a result of second growth trees subsequent to Comstock logging in the late 1800s. Moving quickly toward traditional Sierra Nevada forest structure with predominance of more drought tolerant species may help reduce ET demand and would likely be more resilient to increasing climate variations as well as to wildfire.

Any strategy in forest and soil management that enhances organic matter content of the soils would increase water holding capacity and help maintain infiltration characteristics. This would be relevant to thinning and fire management practices, where controlled burns are perhaps less beneficial in the long run for enhancing percentage and depth of organic content in soils.

Innovations that could be developed to overcome the natural hydrophobicity of surface soil layers in Tahoe forests and other land use areas would improve infiltration rates from brief and infrequent summer showers to help maintain minimal soil moisture levels.

We should also anticipate species shifts that are likely to happen with warming temperatures and drier conditions. There is an expectation, for example, that some oak species may expand into lower ranges of the Tahoe Basin and displace existing stands of white fir and Jeffry pine. It is critical that we evaluate these potential species shifts and plan for their likely consequences, whether beneficial or detrimental. The stimulatory effects of warming temperatures on forest growth are also likely to be a factor in forest changes and soil moisture deficits.

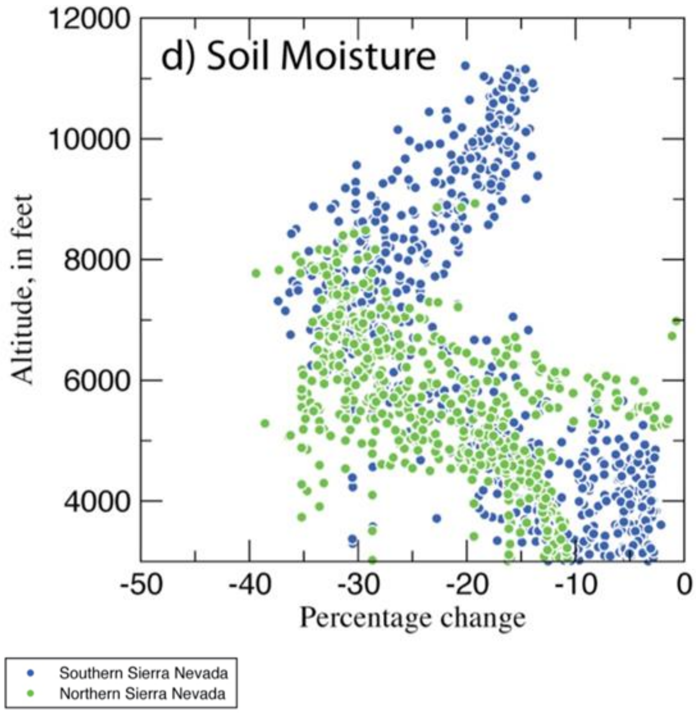

Figure 1. Average projected changes, by 2070-2099, in June-September soil moisture as functions of elevation and subregion in the Sierra Nevada, from the 10-model ensemble of climate models responding to RCP 8.5 as percentage changes from 1961-1990 average condition (from Dettinger et al. 2018).

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Forest Biological Diversity Vulnerability Assessment

Date: March 29, 2019

By: Patricia Manley, PhD, USDA Forest Service, Pacific Southwest Research Station (PSW); Patricia Maloney, PhD, University of California at Davis, Karen Pope, PhD, PSW; Peter Stine, PhD, PSW

RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Forest Biological Diversity

Resource Profile – Summary of Historical, Current, and Future Climate Conditions

- The Basin has a high diversity of species, in part because of its location at the nexus of the two major biogeographic provinces: the California Floristic and the Great Basin Provinces. The Basin supports over 60 vegetation types and upwards of 1,100 species of vascular plants. It also supports a broad array of vertebrate species: 262 birds, 66 mammals, 8 reptiles, 6 amphibians, and 27 fishes.
- These biological communities were impacted by resource use (timber harvest, livestock grazing, and urbanization) and fire suppression policies for almost a century (1850-1950) resulting in the loss of four bird, seven mammal, and one amphibian species and shifting of some pine-dominant forests to largely fir-dominated forests. In addition, old growth forests have declined to less than 2 percent of the land area and reside in 38 small relict stands.
- Since 1950, the Basin has been managed to restore watershed and forest conditions; grazing was curtailed and forest regeneration has been a primary objective. Today, a variety of stressors continue to impact the Basin including urbanization, fire suppression, recreational activities, and climate change.
- Forest management strategies are evolving and trending toward more compatible approaches that promote landscape heterogeneity and the retention and recruitment of older, larger trees.

Resource Sensitivity and Exposure to Climate Change

The Basin has an extensive elevational range (greater than 1,000 meters from Lake Tahoe lake level to the surrounding crests). Climate change has the potential to directly alter the distributions and interactions of many species, particularly habitat specialists and high-elevation associates, which are most at-risk. For example, the pika (*Ochotona princeps*) has already been extirpated from most of its former range (high elevation talus fields) in the Basin. Organisms will respond to climate change in individual and species-specific ways, potentially creating communities that have no historical or modern analogue. These shifts in composition and structure are likely to be accompanied by shifts in genetic diversity and behavior. Fires are also expected to be more frequent and intense under higher average temperature regimes, which will in turn alter forested landscapes and habitat conditions for plant and animal species throughout the Basin.

Impacts and Implications of Climate Change

Many native plant and animal species are likely to experience shifts in abundance and distribution and for some, uncertain persistence. Re-surveys for vertebrates conducted roughly 100 years after original surveys by researchers on the west slope of the Sierra Nevada found the following:

- the elevation limits of geographic ranges shifted primarily upward,
- several high-elevation species (e.g., alpine chipmunk; *Tamias alpinus*) exhibited range contraction (the lower elevational range limit shifted upslope), while several low-elevation species expanded their range upslope,
- many species showed no change in their elevational range,
- elevational range shifts resulted in minor changes in species richness and composition at varying spatial scales,
- closely-related species responded differently to changes in climate and vegetation, and
- most upwards range shifts for high-elevation species are consistent with predicted climate warming, but changes in most lower- to mid-elevation species' ranges are likely the result of landscape-level vegetation dynamics related primarily to historical land-use (e.g., logging and fire suppression).

Invasive non-native species and lower elevation native species that did not historically occupy the Basin could also increase in number and extent, creating stress on historically native species through competition and predation. There are many species of aquatic invasive species that threaten the integrity of the Lake (see elsewhere in this document). Even some terrestrial invasive species such as barred owls, starlings, and white-tailed ptarmigan present a threat to the Basin. Environmental heterogeneity, inherent in the Basin, also has the potential to modulate the response of plant and animal species to rapid environmental change.

Key Elements of Adaptive Capacity and Resilience

Strategic management of populations, habitat, and special habitat features can reduce projected impacts of and facilitate adaptation to climate change. Major adaptation strategies being used in western montane areas include:

- reduce vulnerability to anticipated climate-induced stress by increasing habitat resilience at large spatial scales (see discussion on forest resilience),
- manage for realistic outcomes and prioritize treatments that facilitate adaptation to a warmer climate,
- consider tradeoffs and conflicts that may impact adaptation success, and,
- manage dynamically and experimentally and manage for resilient structure and composition.

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Forest Ecosystem Dynamics Vulnerability Assessment

Date: March 29, 2019

By: Patricia Manley, PhD, USDA Forest Service, Pacific Southwest Research Station (PSW); Patricia Maloney, PhD, University of California at Davis, Karen Pope, PhD, PSW; Peter Stine, PhD, PSW

RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Forest Ecosystem Dynamics

Resource Profile – Summary of Historical, Current, and Future Climate Conditions

- Historical land-use (logging, fire suppression, grazing, invasive species introductions) and anthropogenic climate change have altered the structure and functioning of forest ecosystems. Biotic (insects, pathogens, invasive species) and abiotic (fire, drought, air pollution) disturbances interact with biogeochemical cycles and energy flows. These interactions have the potential to initiate novel successional trajectories across living (plants, animals, microbes) and nonliving (air, water, mineral soil) system components and compromise ecosystem resilience.
- Fire and drought are projected to become more severe and widespread in our future climate. There is also the potential for more widespread insect and disease outbreaks and the accelerated spread of invasive species. Climate change can alter fundamental biogeochemical cycles and atmospheric conditions that can significantly influence carbon storage and subsequent emissions. Warming temperatures will also change plant water-use, which exerts considerable influence on carbon, hydrological cycles, and biotic responses to climate change.

Resource Sensitivity and Exposure to Climate Change

Forest growth is a critical and major carbon sink in the northern hemisphere that has the potential to mitigate the ongoing rise in atmospheric CO2. Hence, predicting forest sensitivity (e.g., resilience, tolerance, susceptibility) and changes in productivity in response to complex and interacting natural and anthropogenic disturbances (e.g., prolonged drought periods, fire suppression and subsequent stand densification, climate-mediated insect outbreaks, disease pressure, climate variability, land-use changes, groundwater depletion, and declining snowpack) is a fundamental challenge to forest ecosystem managers.

Impacts and Implications of Climate Change

Climate change has the potential to compromise vital forest ecosystem functions and processes. For example, drought stress and widespread outbreaks by bark beetles will result in increased tree mortality. Increased mortality and dead wood reflect a gradual loss of sequestered carbon over time and an increase in the risk of high intensity fire, which would result in a rapid loss of aboveground carbon stocks. Biodiversity of native plant species may decline because of reduced moisture across the range of forest types and aspects, given that highest species diversity is typically found in more moist forest environments. However, forests and soils have the capacity to reduce and modulate the magnitude of climate change, if managed carefully. This is especially true in topographic refugia where broad-scale effects of climate change are somewhat mitigated by fine-scale habitat conditions.

Key Elements of Adaptive Capacity and Resilience

Active forest management and monitoring are key to promoting the adaptive capacity and resiliency of forest ecosystem functioning in the Basin. Ongoing effective forest management and restoration of environmental heterogeneity in the Basin has the potential to mitigate the impacts to sudden and prolonged abiotic (e.g., drought and extreme wildfire) and biotic (e.g., pest outbreaks) stressors. Ecological complexity and uncertainty requires developing flexible decision support tools, innovative solutions (e.g., implementation of PSW-GTR-220 concepts), and new private-public partnerships (http://www.blueforestconservation.com).

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Riparian and Aspen Ecosystems Vulnerability Assessment

Date: March 29, 2019

By: Patricia Manley, PhD, USDA Forest Service, Pacific Southwest Research Station (PSW); Patricia Maloney, PhD, University of California at Davis, Karen Pope, PhD, PSW; Peter Stine, PhD, PSW

RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Riparian and Aspen Ecosystems

Resource Profile – Summary of Historical, Current, and Future Climate Conditions

- Riparian systems occur at the interface between uplands and streams or lakes and consist of predominantly hydrophilic vegetation such as willows or alders. Riparian habitats are limited in geographic extent (63 streams flow into Lake Tahoe) but have significant ecological importance because they provide vital connections between the surrounding watershed and the Lake. These systems support diverse and large numbers of animal and plant species, including riparian obligates such as the rare mountain beaver (*Aplodontia rufa*).
- Many riparian areas were severely degraded during the mining era of the late 1800s and extensive sheep and cattle grazing from the late 1800s to early 1900s, but have recovered to various degrees since that time.
- Roads in the Basin continue to impact floodplains, and reductions in beaver populations may have resulted in a more limited extent of riparian habitat. Current threats include the lack of periodic renewing disturbance (fire, flooding), unrestored historical channel alterations, and drought stress.
- Aspen systems are found within riparian areas or along meadows and in stand-alone groves. Aspen stands are relatively uncommon in the Basin (about 2,500 acres) but are an important habitat for many species, and they contribute to the overall diversity of the Basin. Conifer encroachment due to lack of fire, prolonged droughts, and reduced snowpack threaten the long-term vigor and persistence of many aspen stands in the Basin.

Resource Sensitivity and Exposure to Climate Change

Riparian areas are directly dependent on runoff from snowpack in the upper watershed supplying late season moisture to vegetation (see discussion on snowpack, runoff and CWD). Riparian habitat is significantly threatened by increases in temperature and subsequent drought stress; changes in timing, volume, and variability of flows; and increases in fire occurrence and severity.

Encroachment of conifers in the absence of wildfire exacerbates these threats. Aspen is an early seral species (i.e., it is one of the first to appear following a disturbance such as fire or logging) and a poor competitor with conifers. Decline in soil moisture availability threatens aspen groves. Exposure will be site-specific given the variability in micro-environmental conditions in response to lower snowpack and extended dry season.

Impacts and Implications of Climate Change

Riparian systems are currently at risk of wildfire due to high densities of encroaching conifers. Climate change may exacerbate this risk due to increased temperatures and drought stress. However, increased high severity fire in forested areas may paradoxically provide an opportunity for the regeneration of riparian stands and successful aspen migration and establishment (Krasnow and Stephens 2015). Riparian areas may also experience warm low flows and flashier floods, which could result in changes in the aquatic community and increased degradation of susceptible channels.

Key Elements of Adaptive Capacity and Resilience

Riparian systems are adapted to periodic disturbance and thus are capable of rebounding from deteriorated conditions. Strategic use of fire and reduction of conifer density in select locations in the Basin may help sustain riparian and aspen ecosystems. Management of fuel loading, tree density, and forest structure through multi-scale landscape management strategies can optimize opportunities for riparian and aspen establishment, restoration, and maintenance. Stream restoration that raises the water table elevation and increases the area of connected floodplain would result in a wider and more dynamic riparian zone. Efforts to restore aspen should focus on restoring the dominance of aspen in the canopy, prioritized restoration of threatened or damaged stands, and maintenance of the deciduous tree, shrub, and herbaceous vegetation in existing aspen groves.

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Meadow Ecosystems Vulnerability Assessment

Date: March 29, 2019
By: Patricia Manley, PhD, USDA Forest Service, Pacific Southwest Research Station (PSW); Patricia Maloney, PhD, University of California at Davis, Karen Pope, PhD, PSW; Peter Stine, PhD, PSW
RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Meadow Ecosystems

Resource Profile – Summary of Historical, Current, and Future Climate Conditions

- Meadows are important components of the Basin because they act as forest breaks and natural filters of water and sediment. Most of the large, iconic meadows in the Basin were degraded through the mid-19th century due to intensive grazing and human manipulation of drainage patterns that together reduced vegetative resistance and concentrated flow paths.
- Although grazing practices have been curtailed since the 1950s, channel incision and the consequent disconnection of streamflow from the meadow floodplain have persisted, resulting in greatly lowered water tables. In addition, fire suppression has increased densities of lodgepole pine (*Pinus contorta*) surrounding meadows, which reduces runoff and exerts additional seed sources facilitating more rapid conifer expansion onto the drier meadow surfaces (Boisrame et al. 2017).
- Meadow restoration has been a priority in Basin for the past few decades. Many meadows such as Big Meadow, Cookhouse Meadow, and High Meadow have undergone restoration treatments to raise the water table and reconnect it with the meadow floodplain (see Figure 2 for the location of meadows in the Basin). These restored meadows have regained capacity to retain sediment, disperse flood flow, build organic-carbon-accumulating soils, and support diverse animal communities.

Resource Sensitivity and Exposure to Climate Change

Sierra Nevada montane meadows occur in low gradient valleys of watersheds with shallow or impermeable soils where fine sediment accumulates and water collects (Wood 1975, Weixelman et al., 2011). Shallow water tables and high densities of soil carbon and nitrogen allow for lush herbaceous vegetation growth that supports high biodiversity and forage for domestic and native herbivores (Allen-Diaz 1991). Functioning stream-associated meadows also stabilize channel banks, dissipate energy from high flows, filter sediment and enhance groundwater recharge (Peterson et al. 2001, Viers et al. 2013). Wet meadow conditions are dependent on sustained soil moisture, which is directly threatened by larger-scale changes in hydrology suggested by changing climates. For example, many rare meadow forbs are adapted to low oxygen conditions found in prolonged saturated soils, but disappear when soil conditions become drier and are quickly colonized by more generalized grasses and shrubs. See discussions above that detail the likely declines in soil moisture availability in response to changes in snowpack, runoff, and CWD. Mountain meadows have a relatively outsized contribution to the hydrology of the surrounding landscape by slowing the release of snow meltwater downstream (Hammersmark et al. 2008). This reduces flood risk and is ecologically significant to biota dependent on these flows. Intact wet meadows are important groundwater-dependent ecosystems (Figure 1). Meadow hydrology in the Sierra Nevada has historically been altered by anthropogenic activities like logging, road and railroad construction, ditching/channelization and grazing (SNEP 1996, Belsky et al. 1999) and shifts in climatic regimes present a significant future threat. Altered meadow hydrology has resulted in changes in vegetation composition and habitat loss, faster stream flows and therefore a change in timing of water released downstream, stream downcutting and water table depression, conifer encroachment and a gradual loss of meadow extent, aerating of soils and the loss of carbon storage capacity.

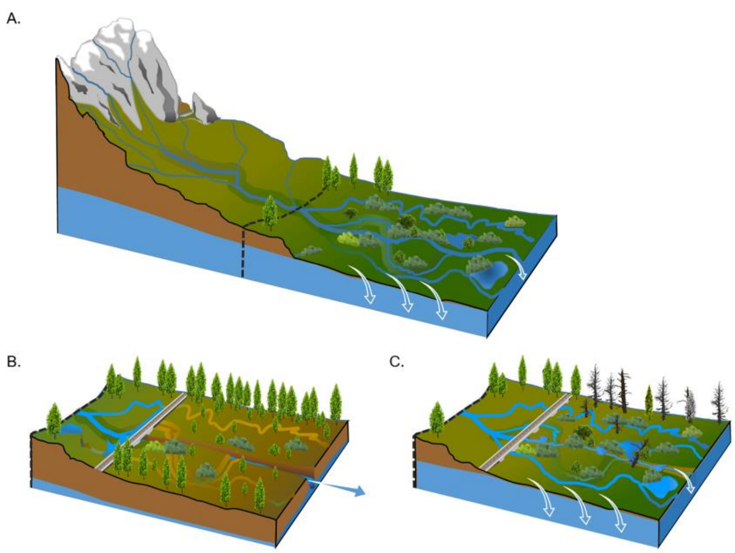

Figure 1. Wet montane meadows are complex habitats often formed in low gradient depressions where ground water is held near the surface and infiltration occurs (A). When degraded, for example due to concentrated flows associated with a road crossing, channels may incise resulting in the drainage of surface and ground water and the transformation of meadow vegetation to more xeric forest and shrub communities (B). Restoration of natural flow paths can restore most of the ecological functions of meadows (C).

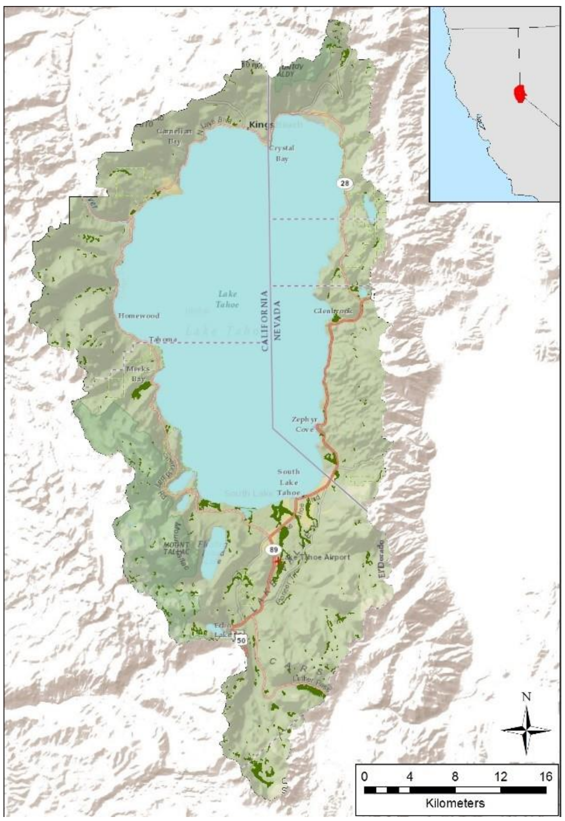

Figure 2. Meadows (dark green) compromise a small proportion of Lake Tahoe Basin but serve as important habitats for a diverse assemblage of plants, pollinators, birds, fishes, and amphibians.

Resource Sensitivity and Exposure to Climate Change

Functioning meadows are expected to serve as a climate refugia for a wide range of bird, fish, and amphibian species because consistent high water tables maintain wet and productive conditions, even during periodic drought conditions. However, recent predictions of meadow resiliency to climate change suggest most Sierra Nevada meadows are not naturally sustainable under the forecasted climate regimes (Lubetkin et al. 2017). Forecasted changes in temperatures and snowpack, discussed above, are likely to reduce water tables to levels that result in the drying of many meadows for prolonged periods. If this happens for any given meadow in the Basin it will likely result in conversion to forest or shrubs. Meadows that have consistent groundwater input are inherently more resilient to changing climate conditions, such as prolonged drought, than snowmelt-dominated systems and, as such, may be good candidates for restoration and conservation.

Impacts and Implications of Climate Change

The impending reduction in snowpack, and changes in runoff patterns and resulting CWD, as discussed above, escalates the importance of recovering functioning meadows in the Basin. While the existing meadow restoration projects can serve as guides for achieving successful restoration, improvements to restoration design are still needed to better integrate system-wide fluvial processes, address root causes of degradation, and minimize detrimental disturbance to meadow surfaces. Without restoration, climate change is expected to continue the conversion of meadow habitat to upland forests (Lubetkin et al. 2017).

Key Elements of Adaptive Capacity and Resilience

Once channels become incised, natural recovery often results in a more constricted floodplain within a widened and deepened channel bed. Recent advances in ecologically based restoration design demonstrate that strategically placed biogenic structures, such as beaver dam analogs (Pollock et al. 2014), can accelerate physical and biological processes to restore and enhance meadow function. This technique creates conditions favorable to beaver, encouraging them to take over restoration and maintenance (Figure 3). Sierra Nevada meadows were historically stable systems (Wood 1975). Therefore, an approach to restoration that recovers innate resiliency and is self-sustaining may safeguard meadows from the impacts of climate change.

Figure 3. Beaver dams at Last Chance Creek aid in meadow restoration by reducing stream power, trapping sediment, and creating conditions favoring the growth of emergent and riparian vegetation that can resist erosive flows. Note the sagebrush on the historical meadow floodplain.

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Wildlife Connectivity Vulnerability Assessment

Date: April 16, 2019

By: Peter Stine, PhD and Patricia Manley, PhD; USDA Forest Service, Pacific Southwest Research Station

RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Wildlife Connectivity

Resource Profile – Summary of Historical, Current, and Future Climate Conditions

Landscape connectivity is a vital element of conservation strategies throughout the world. Connectivity is generally defined as the degree to which the landscape facilitates or impedes movement of plants (propagules) and animals. This includes both "structural connectivity" which is simply the recognizable (and mappable) features of the landscape (habitat type, trees, rocks, streams, etc.) as well as the "functional connectivity" which reflects how a given species utilizes particular aspects of a landscape for safe and effective movement. Connectivity operates at a number of scales: movement occurs both at very small scales (e.g., within and among adjacent watersheds), intermediate scales (across multiple watersheds), basin-wide scales, and across the basin as part of larger landscape movement phenomena. Landscape linkages also provide for various kinds of movement, including dispersal (one way movement for individuals), migration (seasonal movement), and commuting (daily movements). In some cases landscape changes can create linkages that are ecologically detrimental, such as expanding ranges of non-native species in response to landscape fragmentation.

Landscape linkages, particularly the notion of a wildlife corridor, are commonly thought of as linear features (e.g., streams, riparian corridors). However, a linkage can also consist of stepping stones (e.g. a series of nearby, similar patches) or habitat mosaics (e.g. mosaics of different seral stages of forest). Linkages can also be landscape features that facilitate ecological processes such as predator-prey interactions, nutrient and energy flows, pollination, and other processes that are affected by landscape connectivity. Effective connectivity is a very species or process specific feature. For example, movement of a species such as a Steller's jay, which uses many types of habitats and is minimally impacted by human presence and fragmentation. By contrast, movement of marten which are typically found in higher elevation forests infrequently traverse wide openings, such that reductions in forest connectivity could affect the connectivity of their population.

The Lake Tahoe basin, like all landscapes, is inherently variable containing a patchwork of different ecological features (e.g. degree of slope, vegetation type, streams, lakes, precipitation, temperature variation, etc.) and several elevational zones that have different suitability and movement affects for animals, plant propagules, and processes. In addition, vegetation in the Lake Tahoe basin changed dramatically during and after the Comstock mining era in the late 1800s and early 1900s, with widespread tree removal, followed by subsequent regrowth and fires suppression. The result is a present day landscape with relatively homogeneous, contiguous mid-seral forests with few trees over 100 years old. Contiguous mid-seral forests result in high connectivity for most forest associated species within elevation zones and along elevational gradients within watersheds. However, the deficit in old, large trees, particularly in lower elevation zones, is likely to limit resting, denning, and roosting structures that facilitate larger-scale movements for wide-ranging old-forest associated species, such as American marten.

Connectivity in the basin is also affected by fixed physical and anthropogenic features. The crests of the Sierra Nevada and Carson Ranges that surround the basin serve as barriers to immigration of plants and animals into the basin as a function of significant climatic and vegetation barriers at the higher elevations. As a result, the lower elevation passes across these ranges serve as the primary corridors for immigration into the basin for plants, animals, and people (who are also vectors for immigration into the basin). These passes are also the location of the primary highway transportation corridors into and around the basin (U.S Highway 50, California State Highways 89, 28, 267, and Nevada Highways 28, 431, and 207). Roads are well known to be a significant barrier for certain species, particularly those that are otherwise highly mobile over large areas such as black bears, mountain lions, marten, bobcats, and deer. These species are vulnerable to wildlife-vehicle collisions, and high traffic levels—median barriers and other physical structures associated with roads exacerbate this risk. Smaller and slower moving species such as reptiles and amphibians are more vulnerable to wildlife-vehicle collisions, particularly during dispersal periods.

In terms of human development, the primary population centers are located around the circumference of the Lake along the primary highways (many smaller communities), and close to the five primary transportation corridors connecting to population centers outside of the basin: South Lake Tahoe, Lake Tahoe, and Meyers in the South, and Tahoe City and Incline Village in the north. Current policies have strict limits on additional building in the basin, so the assumption is that the footprint of urbanization will not expand, although it is likely that additional transportation mechanisms are likely to be developed (e.g., a rail system, electric cart network) to accommodate growing visitation and car traffic problems.

Exposure and Sensitivity to Climate Change

Terrestrial habitats throughout the basin will be exposed to warming conditions and changes in precipitation regimes (see discussion under projected changes in climate and terrestrial systems). The resulting direct habitat loss and accompanying habitat fragmentation are likely to have an impact on the connectedness of many habitat types, but it is difficult to predict what changes will have the greatest impact.

Warmer and more variable temperatures are expected to be primary characteristics of future climates. Prolonged warmer temperatures and spikes in temperature may initially push species to higher elevations, and habitat connectivity will be important to enable species to make elevational adjustments. Species that are on the edge of their ranges, particularly more cold-adapted species at the warmer edges of their ranges are likely to be the most sensitive to warming climates. In addition, higher temperatures may facilitate species coming into the basin that otherwise might not have been able to tolerate the historically colder climate, essentially creating or strengthening connectivity for species and populations previously only occurring outside the basin, including non-native species and highly adaptable and competitive generalist species. Reduced precipitation and greater variability in the magnitude of precipitation events could reduce some of the flow of individuals coming in from outside the basin, but it is not likely to entirely counter the effects of increasing temperatures. Species that are less tolerant of warmer water temperatures will also be among the most vulnerable, specifically species associated with limited alpine environments may experience significant habitat loss and fragmentation.

Further, reduced precipitation is likely to affect the connectivity of aquatic organisms associated with streams, lakes, ponds, aspen stands, and meadows through reduced flows, and reduced duration of ponding and saturated conditions. Meadows, for example, are expected to be highly vulnerable. Recent studies suggest that two thirds of the meadows along the west shore of the basin may not be able to provide adequate refugia for meadow species under future climate scenarios because of reduced connectivity and wetness, and the west shore is the most mesic part of the basin.

Future warming and drying also are likely to exacerbate existing vulnerabilities. For example, studies show that currently about 80% of streams in the west shore have barriers to aquatic organism passage and nearly half (47%) of the streams contain more non-native than native aquatic species, again representative of the basin as a whole. Non-native species are frequently adaptable generalists and fair better in altered environments, making native species even more vulnerable to expanded populations and increased competition from non-native species that may be better able to persist in more fragmented systems. Another example of existing exposure is high density of roads and trails in the basin, particularly at lower elevations and on the more populated west side of the basin. Specifically, 75% of the west shore landscape is within a quarter mile of a road or trail. As climates warm and human populations outside the basin grow, it is anticipated that visitorship will increase, resulting in additional disturbance near roads and trails, many of which traverse otherwise connected vegetation conditions.

Impacts and Implications of Climate Change

With this backdrop of current conditions in the basin and ongoing changes to climate there is a potential threat to key linkages located in or near habitat considered at risk to warming and changes in precipitation regimes. Every species has a unique response to climate change, but in general as important linkages degrade, population sizes are increasingly vulnerable to reductions because of reduced immigration rates and stability is challenged by possible reductions in genetic diversity. Climate change is likely to favor non-native species and generalist native species, which pose threats to the biological diversity and functional diversity within the basin. Some species may shift in their resource use, as opposed to changing their occurrence or distribution in the basin. For example, the black bear may respond by shifting to even greater reliance on human food sources and seeking human structures for resting and denning, if upslope food sources become more scarce.

Key Elements of Adaptive Capacity and Resilience

Linkages between lower and upper elevations will be important to facilitate species staying within climate conditions to which they are adapted. Similarly, removing aquatic barriers for native species will facilitate greater movement upstream if water temperatures rise beyond species tolerances. Protecting connections for sustaining genetic diversity could include maintaining interbreeding within the geographically dispersed population (for example Sierra Nevada yellow-legged frogs) or indirect maintenance of genetic diversity through landscape heterogeneity and permeability for pollinators.

The most vulnerable linkages are likely tied to those species considered to be at risk for other reasons. It would be prudent to catalog the plant and animals species found in the basin that are considered at risk either locally, regionally, or even nationally. By evaluating those species and their habitat requirements (along with continued monitoring programs) managers can then focus on conserving or restoring the elements of their habitat that enable movements essential to their life history (e.g., large trees with broken tops, cavities, or other features that provide nesting and roosting platforms).

It is important to identify migration pathways and other locations that are critical to wildlife movement patterns. In some cases this information may already exist (e.g. deer migration routes), but in many cases it does not. For example, stream courses are often used by many species of wildlife for movement corridors. Dense vegetation along streams often provide the cover needed for movement by different species. Dirt roads and trails can also serve as important movement corridors for larger animals, such as bears. Existing data and modeling can help identify known or suspected features that are important to wildlife, which then can be targeted for appropriate maintenance and management (to the degree possible), and also monitoring, in order to maintain their value as a linkage. Existing data and modeling can identify key locations for potential use of measures to mitigate wildlife mortalities due to road collisions. Certain locations along may be key crossings for mule deer, black bear, mountain lions, and other species which tend to move long distances. Such measures include posting of warning signs and use of wildlife crossing measures such as bridges/overpasses, underpasses, culverts, fencing, reflectors, and lighting.

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Public Health Vulnerability Assessment

Date: May 20, 2019
By: Sam Evans, Tim Holland, Matthew Potts (University of California, Berkeley)
RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Public Health

Climate change will create several public health challenges across California and within the Tahoe Basin. In the Tahoe Basin, increasing wildfire and related smoke exposure and greater heat-related mortality and morbidity are of greatest concern. In an indirect way, food insecurity, direct and indirect health-related impacts of drought, food- and water-borne illnesses, compounded health issues from air pollution, and adverse mental health outcomes may also negatively impact human well-being in the Tahoe Basin.

While all individuals are susceptible to many of the health risks posed by climate change, certain subpopulations are at particular risk. The elderly, young children, and individuals with pre-existing medical conditions may be more adversely affected from extreme heat events and wildfire smoke exposure than other groups. In addition, individuals working in outdoor occupations are also at particular risk of extreme heat events. Socio-economic factors also affect a population's health risk. For example, individuals that are physically and socially isolated may not have the means to adequately respond to extreme weather events. Low-income workers may not be able to afford mitigation efforts such as taking time off work.

Impacts, Hazards, and Threats of Climate Change(s) to Resource/Value

Health Effects of Wildfire Smoke: There is scientific consensus that smoke exposure poses several direct threats to human health. Across the general population wildfire exposure has been associated in numerous studies with adverse respiratory outcomes, such as asthma. More recent studies have also found an elevated risk of cardiovascular and cerebrovascular conditions, all-cause mortality, and evidence of adverse birth outcomes from smoke exposure. However, differential health risks from wildfire exposure across specific age, pre-existing health condition, socioeconomic status, and ethnicity have not been conclusively shown and remain an area of active research. In addition, most work to date has focused on the health impacts of large wildfire events, rather than lower level smoke exposure from prescribing burning activities, although this is an area of active research.

Health Effects of Extreme Heat Events: Increasing frequency, intensity, and duration of extreme heat events pose a serious public health risk, including both elevated heat-related morbidity and mortality from heat stroke, exhaustion, and dehydration. This association has been well documented across a variety of geographies and populations and will likely pose a growing risk to communities in the Tahoe Basin as the number of extreme heat events increases. For example, a study of the 2006 California heat wave found significantly elevated risk ratios (7.35-8.56 in counties around the basin) for heat-related hospitalizations (Figure 1). It is also important to note that there is a potentially adverse interaction between extreme heat events exacerbating the public health effects of wildfire smoke exposure in the Tahoe Basin as extreme heat and wildfire events both increase over time due to climate change Research has already made this connection in urban environmental with non-smoke pollution.

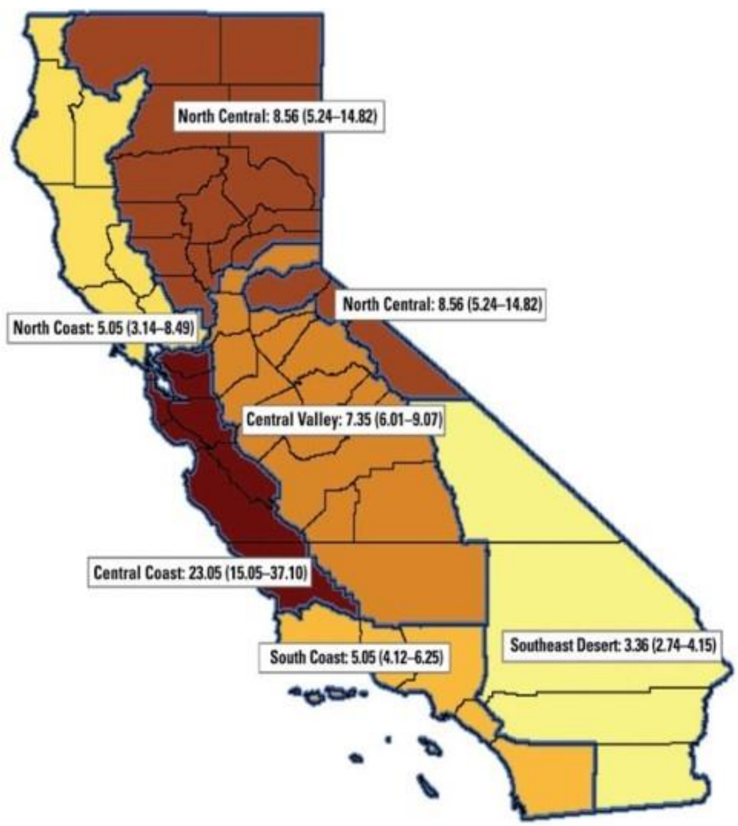

Figure 1. Risk Ratios for Heat-Related Emergency Department Visits During the 2006 California Heat Wave (Knowlton et al. 2009)

For vulnerable/isolated individuals and communities that are not well adapted to temperature extremes this risk is of special concern. The California Heat Assessment Tool projects that census tracts in the Tahoe Basin are relatively less likely to experience extreme heat events than other regions of California (Figure 2); however, an elevated number of events are expected to occur in counties around the Basin, especially in the latter half of this century. Research has also found that extreme-heat events have disproportionately adverse effects on elderly and infant populations, socially or geographically isolated populations, and individuals working in temperature-exposure occupations. All these populations are represented in the Tahoe Basin (Table 1). In fact, according to the California Heat Assessment Tool, several census tracts around Lake Tahoe have 10-15% of their workforce in outdoor occupations. This is well-above the state average and thus indicate an important public health vulnerability.

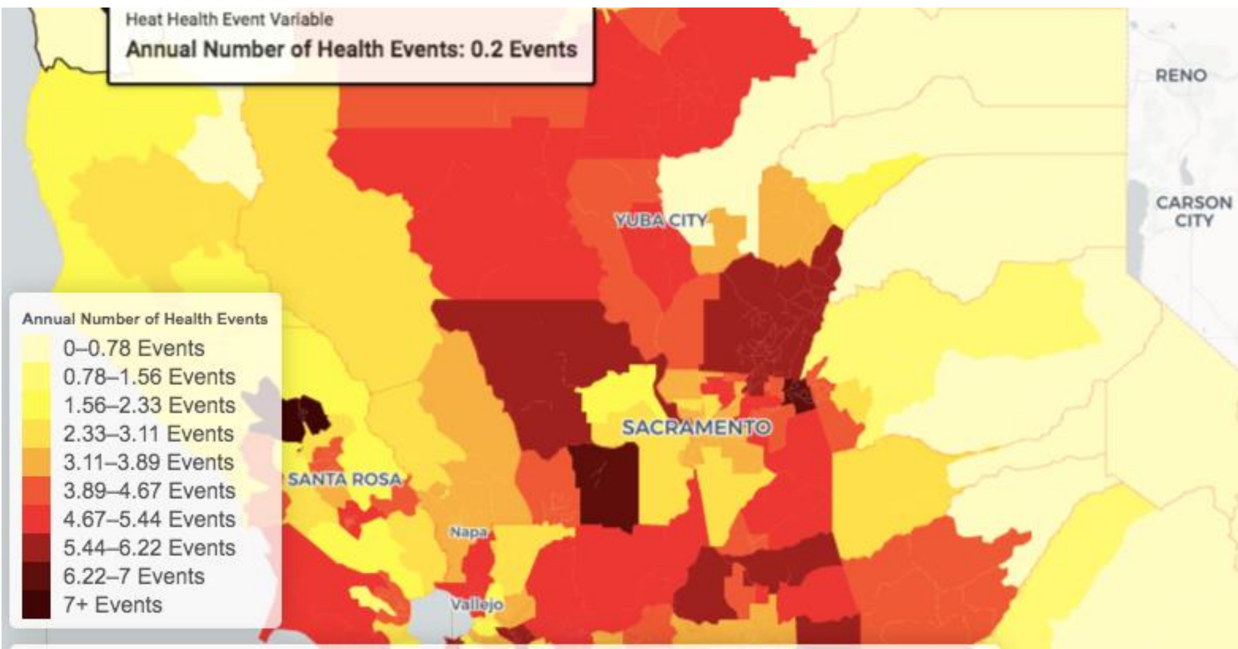

Figure 2. Projected Number of Extreme Heat Health Events (2041-2060), (California Heat Assessment Tool)

Adverse public health outcomes from extreme events will also strain the capacity of the region’s public health system. Extreme climate events are likely to increase hospital admissions and create additional need for emergency response services. If local institutions are not adequately prepared for these events, additional adverse health outcomes are possible due to the added strain on the community’s public health resources.

Key Elements of Resource's Adaptive Capacity and Resiliency: Adverse public health outcomes from climate change are not a foregone certainty and depend largely on individual and institutional resiliency. Widespread use of adaptive measures, such as increasing availability air conditioning (for extreme heat events) and better air filtration systems (for wildfire smoke exposure) would help to mitigate some of the aforementioned health risks. Institutional resiliency through rapid and reliable surveillance of extreme climate threats, such as wildfire, smoke-related, and extreme heat monitoring and warning systems would also mitigate some of the health risks identified above. However, in the Tahoe Basin, reaching isolated or vulnerable communities will continue to be a challenge. Research also suggests that California communities that are adapted to moderate climate conditions may be at particular risk, especially in the short term, as extreme heat events become more common. While research has highlighted this risk for coastal communities, the issue may also be relevant to the Tahoe Basin where extreme heat events are likely to become more common. Identifying vulnerabilities, creating community awareness, establishing effective partnerships, and adequately funding climate and health programs are all essential in facilitating adaption to the Tahoe Basin's increased risk of public health challenges related to climate change

Table 1. Climate Change and Health Vulnerability Indicators for El Dorado and Placer County

Category	Indicator	Description	El Dorado County	Placer County	California Average
Environmental Exposures	Extreme Heat Days	Projected number of extreme heat days (2035-2064)	42.4	43.5	31.9
	Air Quality (PM2.5)	Annual Mean Ambient Concentration of PM2.5	6	7.3	7.7
	Air Quality (Ozone)	3-year ozone concentration exceedance	0.18	0.12	0.07
	Wildfires	% of population currently living in very high wildfire risk areas	39.50%	9.10%	12.20%
Population Sensitivity	Children	% of population age less than 5 years	5.30%	6%	6.40%
	Elderly	% of population aged 65 years or older	14.60%	15.40%	13.70%
	Poverty	Poverty rate	7.90%	6.60%	14.20%
	Education	% of adults with less than HS education	7.30%	7%	17.50%
	Outdoor Workers	% of population employed and aged > 16 working outdoors	6.30%	5.50%	9.70%
	Vehicle Ownership	% of households with no vehicle ownership	3.30%	3.80%	6.30%
	Linguistic Isolation	% of households with no one aged > 14 years speaking English	2.00%	2.60%	6.70%
	Physical Disability	% of population with a disability	5.70%	5.80%	7.40%
	Mental Disability	% of population with a disability	4.50%	3.80%	5.20%
	Health Insurance	% of adults (18-64) without health insurance	10.20%	9.90%	16.40%
	Violent Crime Rate	Number of violent crimes per 1,000 population	2.2	1.8	4.1
Adaptive Capacity	Air Conditioning	% of HH without air conditioning	11.10%	10.30%	36.40%
	Tree Canopy	% without tree canopy coverage (population-weighted)	63.70%	80.70%	84.10%
	Impervious Surfaces	% impervious surface cover (population-weighted)	16.40%	35.80%	33.60%

Source: California Department of Public Health's Office of Health Equity

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Washoe Cultural Resources Vulnerability Assessment

Date: May 17, 2019
By: Jonathan Long, PhD, USDA Forest Service, Pacific Northwest Research Station
RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Washoe Cultural Heritage

Climate change may affect important aspects of the Washoe Tribe's cultural heritage in the Lake Tahoe Basin (Basin). This brief draws upon several recent synthesis reports as well as documents prepared by staff of the Washoe Tribe. The Tribe is preparing its own climate change action plan that addresses similar concerns for their area of interest, which includes but extends beyond the Basin.

Important Elements of Cultural Heritage

Tribal cultural heritage includes plants, wildlife, artifacts, places, sense of well-being and other less tangible values [2]. The term "cultural heritage" avoids the more narrow economic connotations of the terms "resources" and "ecosystem services", which some indigenous people disfavor [3]. These elements are important to the Washoe economy, but they have much broader significance to Washoe well-being. The Washoe, like many indigenous groups, are particularly concerned with the potential of climate change to impact water, food, medicines, and traditional knowledge. Specific elements that have been especially important to the Washoe Tribe include:

- High quality water--Washoe consider it to be the most sacred resource.
- High quality air.
- Native fishes, especially Lahontan cutthroat trout (*Oncorhynchus clarkii henshawi*) and whitefish (*Prosopium williamsoni*), which were harvested at family fishing grounds in Lake Tahoe streams.
- Shellfish, described as "oysters" in some historical texts, which likely refer to the native Western pearlshell mussels (*Margaritifera falcata*) that still occur in the Upper Truckee River.
- Terrestrial wildlife including mule deer (*Odocoileus hemionus*), chipmunks (*Tamias spp.*), snowshoe hare (*Lepus americanus*), white-tailed jackrabbit (*L. townsendii*), swallows (*Hirundinidae*), Belding's ground squirrel (*Urocitellus beldingi*), eagles and

hawks (*Accipitridae*), bear (*Ursus*), flicker (*Colaptes auratus*), grouse (*Dendragapus fuliginosus*), quail (*Oreortyx*), and many others that were used to support traditional lifeways.

- Plants of high cultural importance, many of which were foods, basketry material, and medicines. Species include sedges (*Carex*), bracken fern (*Pteridium aquilinum*), wyethia (*Wyethia*), serviceberry (*Amelanchier spp*.), mountain rose (*Rosa woodsii*), willow (*Salix spp*.), strawberries (*Fragaria spp*.), elderberries (*Sambucus*), tobacco (*Nicotiana*), and many others used for tea, medicine, and foods.
- Historical artifacts, including bedrock mortars, rock art, tools, dwellings, and other evidence of past habitation.
- Sense of place and associated cultural identity and mental health. Lake Tahoe is the center of the universe to the Washoe, and the ancient cultural connections to places in the basin reinforce tribal cosmology and are important to Washoe identity.
- Traditional knowledge and cultural practices that need to be actively applied to sustain or build community capacity to thrive.

Historic and Current Conditions and Trends

- Lake Tahoe is the center of aboriginal territory of the Washoe Tribe. The forced removal and relocation of the Washoe Tribe to reservation lands have impacted the relationships between the Tribe, the Basin, and its associated natural resources. That disruption has impacted the Tribe's traditional practices, economy and lifeways (social systems), and also affected the environment in the basin (ecological systems), including declines in various species, including the grizzly bear, wolf, and Lahontan cutthroat trout.
- Seasonal movements of Washoe people, including moves to and from summer camps around Lake Tahoe, provided an important means of responding to changes in climate; that source of adaptive capacity has been greatly impacted by removal and settlement on reservation lands.
- Indigenous burning was an important part of the frequent fire regime and was common in the fall as Washoe moved to lower elevations to live during the winter. Such practices have largely been extinguished, aside from limited understory prescribed burning conducted by local agencies, particularly for fuel hazard reduction.

- Many traditional foods and other resources important to Native Americans are no longer harvested, due to the combination of many factors, including reduced availability, reduced access, and disruption of traditional activities and knowledge.
- The Washoe Tribe is restoring and maintaining cultural heritage practices in the Tahoe basin through partnerships with federal and state agencies. These efforts constitute adaptive capacity; however, the diminished presence of the Tribe constrains such opportunities. To avoid eroding adaptive capacity, adaptation efforts need to avoid extractive approaches that erode trust and local knowledge in local communities, in favor of co-production.

Warming, Longer Growing Seasons, Reduced Snowpack, Drought, and Increased Wildfire Activity are Likely to Negatively Affect Culturally Important Plants and Wildlife

- Reduced availability of traditional foods: Increased temperatures, longer growing seasons, reduced snowpack, and drought may reduce water levels in springs, streams, and wetlands, and increase moisture stress for many plants, especially in the summer. Such effects could limit plant regeneration and reliable production of fruits such as berries. Although longer growing seasons could result in more crops of some plants, those additional crops may not be high quality. Increased shading from taller shrubs or trees may depress berry production, and warming may accelerate rotting of fruits.
- Upward expansion of species: Climate change may also allow some culturally important plants, such as California black oak and pinyon pine, to increase within the basin as they expand upward in elevation, but those tree species require many decades to establish, mature, and produce nuts, so such potential shifts are unlikely to offset losses in forest food productivity.
- Reductions in snow-dependent wildlife: Some wildlife species associated with cold climates and snow conditions (e.g., snowshoe hare, pika, and wolverine) are already quite rare and may continue to decline.
- Impacts from changes in disturbances on important species: Climate change is expected to lead to more large and/or high severity fires and other tree-killing disturbances (such as large beetle outbreaks). These trends are exacerbated by a legacy of suppressing wildfires and excluding indigenous burning. Intense fires can have negative effects on cultural heritage by causing mortality of important plants, soil erosion, loss of seedbanks, and consumption of legacy trees, snags, and

downed wood. Intense wildfires and drought could reduce the abundance and quality of plants including traditional food, medicinal, and artisanal plants. However, many culturally important plants can resprout (e.g., strawberries, willows, bracken fern, sedges, cottonwoods, and aspen) or reemerge from soil seedbanks following fire (e.g., tobacco). Important plants may be favored by disturbances that consume tree litter, reduce transpiration and snow interception by conifers, and increase understory light. Cultural heritage, including flora and fauna, may be favored if disturbances result in greater heterogeneity at fine scales (e.g., patchy burns), but may be disfavored by more homogenous vegetation in large high-severity burn patches. The negative impacts of climate change are likely to be more pronounced where plants are not actively tended to sustain vigorous growth and productivity.

- Degraded water quality and aquatic habitat: Severe wildfires can degrade water quality and aquatic habitat for fishes and mussels, in particular by triggering meadow incision and streambank erosion, and by extirpating isolated populations of native organisms. However, wildfires can also rejuvenate habitats and extirpate nonnative fishes, so such events could also present opportunities to actively promote cultural heritage through ecological restoration.
- Damage to historical sites: While low-intensity fires are generally desired, more intense fires could cause large trees to fall and burn, contribute to extreme soil heating, and increase soil erosion; such effects can damage archaeological artifacts and cultural sites.
- Reduced visitation (including recreation): High-severity fires may deter Washoe people from visiting areas due to both safety concerns and impacts to sense of place, especially when areas become less recognizable or cultural sites are damaged.
- Constrained opportunities for traditional practices: Climate change may reduce access to desired resources and increase barriers to traditional activities such as burning. In particular, shifting fire regimes may limit opportunities for prescribed fire use (by agencies) and cultural fire use (by tribal members), by increasing the risks associated with such intentional burns, shortening the windows for such burns, and eroding public tolerance of smoke. Furthermore, changes in climate and increased disturbances from wildfires may facilitate spread of invasive plants like cheatgrass, which could complicate efforts to reinstitute traditional burning practices.
- Reduced air quality and health: Large, severe wildfires are expected to increase and to generate poor air quality both within the Basin and in downwind Washoe communities. Such episodes could negatively affect health of tribal members, who

may be particularly vulnerable due to housing conditions (e.g., lack of air conditioning), pre-existing health conditions, demographics (youth, elderly), and low income (making it more difficult to avoid smoke).
- Threats to diet and health: Reduced access to traditional foods, opportunities for cultural practices, and culturally important places may impact food security and associated physical and mental health.

Summary

Climate change is expected to negatively affect a wide range of values that are important to Washoe cultural heritage by intensifying natural disturbances and warming conditions. However, such effects could be mitigated, and increases in disturbances such as fire could be restorative, through active management with concern for Washoe heritage values and direct tribal involvement. Establishing formal partnerships with the Tribe built upon government-to-government, co-production, and co-management frameworks can overcome threats to cultural heritage in the Tahoe basin.

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Lake Tahoe Surface Elevation Projections

Date: October 4, 2019

By: Shane Coors, Precision Water Resources Engineering

RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Washoe Cultural Heritage

Introduction

In addition to possessing enormous environmental, recreational, and cultural value, Lake Tahoe also serves as an important water supply reservoir for the Tahoe, Truckee and Carson river basins. Lake Tahoe's relatively small dam impounds up to 6.1 vertical feet of water which amounts to 744,600 acre-feet and approximately 68% of the total reservoir storage capacity in the Tahoe/Truckee system. With an average annual release of 235,000 acre-feet, Lake Tahoe is the single largest water supply source in the Tahoe/Truckee system, accounting for 43% of the total water supplied from all seven Truckee Basin reservoirs.

What makes Lake Tahoe so unique among water supply reservoirs is its massive surface area (approximately 120,000 acres) and very shallow depth (6.1 feet). Recent research has determined that, on average, approximately three and a half feet of water evaporate from the surface of Lake Tahoe each year (Huntington and McEvoy, 2011). This amounts to more than 400,000 acre-feet, which though small compared to the total volume in the Lake, represents more than half of the total reservoir capacity. Because of the disproportionate influence of evaporation on its water balance, Lake Tahoe is uniquely and highly susceptible to changes in evaporation, which is one of the primary effects expected in a warming future climate. Relatively small changes in future evaporation rates and average inflow volumes can result in substantial changes to the ongoing water surface elevation of the Lake.

Lake Tahoe has a natural rim at an elevation of 6,223 feet above sea level. When the Lake's surface elevation drops below the rim no water can be released through the dam, and the Truckee basin downstream enters drought operations. Furthermore, the Lake is operated to, as far as is practicable, keep the surface elevation below 6229.1 feet in order to preserve the lakeshore environment, to protect lakeshore structures, and to limit erosion. As can be seen in Figure 1, the range of historical pool elevations of the Lake is relatively small and stays between these limits the majority of the time.

Changing climate, however, is introducing changes to the Lake's inflow volume as well as to its evaporation. Increases in evaporation and decreases in inflows contribute to lower lake elevations and possible extended periods during which the surface of the Lake is below its rim, causing significant water supply impacts. Decreases in evaporation and increases in inflows contribute to increase the Lake's elevation, resulting in more frequently exceeding the maximum legal limit which would affect the Lake's shoreline environment.

Study Description

A modeling study was performed to assess the potential effects of climate change on the Lake Tahoe water surface elevation. Eight Global Climate Models (GCMs) were used with two Representative Concentration Pathway (RCP) scenarios (RCP4.5 and RCP8.5) to generate potential future climate conditions for the study. The GCMs were chosen based on their previous identification for applicability to the Tahoe region (Lynn et al., 2015), and their compatibility with the hydrology models. The climate conditions from these GCMs were used as input to hydrologic models of Lake Tahoe and the Truckee River basin (Rajagopal et al., 2015). The GCM outputs were also used to calculate open water evaporation for Lake Tahoe with the CRLE model (Huntington and McEvoy, 2011). The precipitation, streamflow, and evaporation time series produced by the climate, hydrologic, and evaporation models were then used as input to the Truckee River Planning Model, which simulates the operation of Lake Tahoe and the Truckee River Basin system according to its current policy (TROA). The modeling projections extend out to the year 2098.

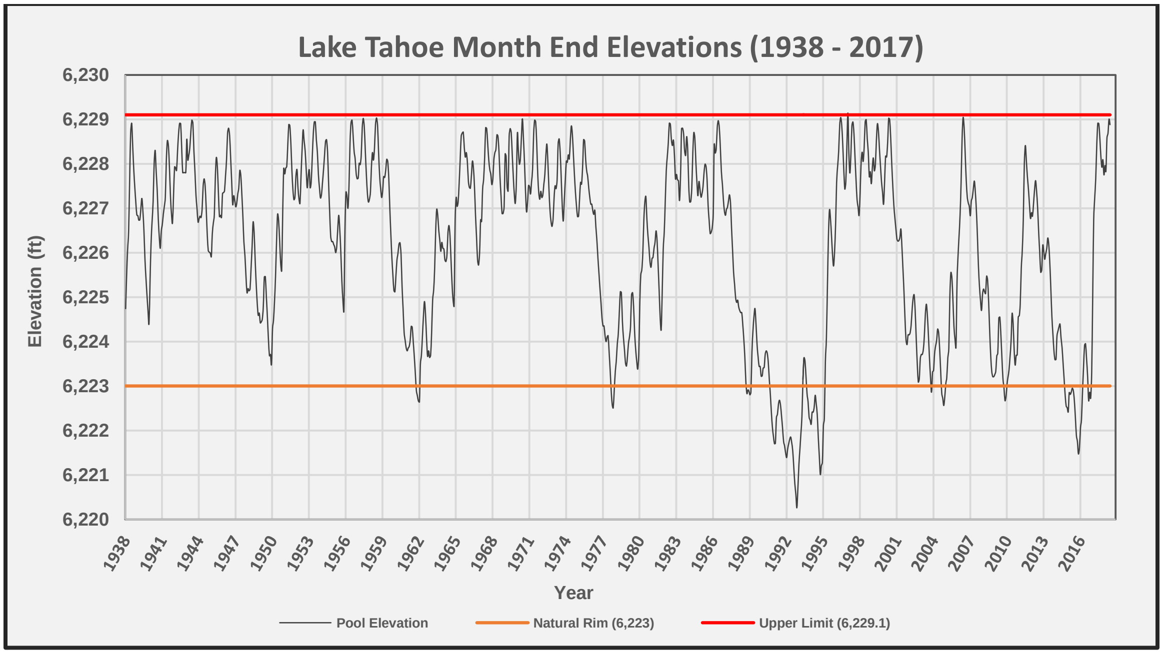

Figure 1 - Historical month end Lake Tahoe pool elevations for the years 1938 to 2018 plotted with the Natural Rim pool elevation (6,223 feet) and the legal Upper Limit pool elevation (6,229.1 feet).

Lake Surface Elevation Results

A portion of the summary results of the modeling study are shown in Figure 1. Lake Tahoe's water surface elevation typically peaks in the summer months after the snowmelt has begun to subside and the evaporation from the surface of the Lake overtakes the inflows to the Lake from the surrounding Tahoe basin. The figure shows a histogram of the peak annual water surface elevation of the Lake for the historical record, and the two RCP ensembles of climate projection runs. Historically (1938-2017) the annual peak water surface elevation of the Lake most often fell in the upper half of the operable range (~71% of years) and next most often in the lower half of the operable range (~23%). The Lake peaks below the rim in only 5% of years and above the rim in just 1% of years. Clearly, since 1938, the water surface of Lake Tahoe is most often in its 6.1 foot operable range with water stored behind and being released through the dam.

In the two ensembles (RCP4.5, RCP 8.5) of future projections of climate and Lake Tahoe operation, there is a clear shift. Generally, the results show that the water surface of Lake Tahoe will more frequently be outside of the operable range than during the historical period. There is projected to be a small increase in the frequency of the annual peak elevation being below the Lake's rim. There is projected to be a significant increase in the frequency of the annual peak being above the maximum legal elevation limit of 6229.1 ft. This is due to an increased frequency and magnitude of storms being projected by the GCMs in the coming decades. With large inflow events, the relatively small dam at the Lake's outlet is physically unable to release at a rate that prevents the water surface from exceeding this limit. This will result in the elevation of the Lake being above the legal limit much more frequently, causing a variety of impacts to the lakeshore environment. This is a condition that is unfamiliar to the Tahoe basin as the last time Lake Tahoe was more than a tenth of a foot over its legal limit was over a century ago. The climate change projections show that the Lake's water surface may be over its maximum legal limit one to two times every decade, and this could have a variety of significant impacts around the entire Lake.

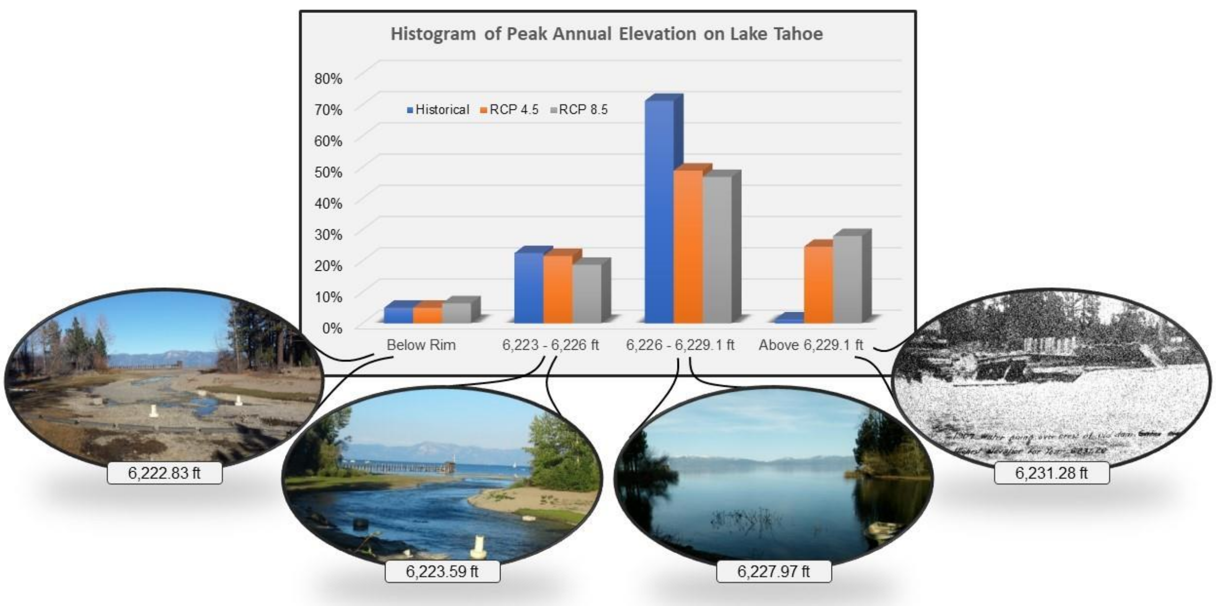

Figure 3. Histogram of annual peak lake surface elevations for the historical period, and the RCP4.5 and the RCP8.5 ensembles of model runs. The elevation range was divided into four bins, 1) below the rim, 2) the lower half of the operable range (6223 ft – 6226 ft), 3) the upper half of the operable range (6226 ft – 6229.1 ft), and 4) above the legal limit.

Recreation Resources Vulnerability Assessment

Date: May 17, 2019

By: Patricia Winter, PhD, USDA Forest Service, Pacific Southwest Research Station

RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Recreation

Summary of Historic and Current Conditions, and Trends

The Lake Tahoe Basin (Basin) offers a diversity of outdoor recreation and nature based tourism opportunities across federal, state, and regional settings. These resources provide essential support to the local, regional, and state economies. Outdoor recreation in 2015 and 2016 represents about 2 percent of the nation's gross domestic product, and the outdoor recreation economy grew at a faster pace during the same period than the nation's economy overall. The National Visitor Use Monitoring Program (NVUM) round 4 data collected in 2015 showed an almost equal distribution of recreation visits to the Lake Tahoe Basin Management Unit (LTBMU) for warm-weather (42.3%) and winter activities (41.4%). In that survey warm-weather main activities were viewing natural features (20.3%) and hiking/walking (13.6%). Winter main activities were downhill skiing (41.3%). Estimated annual expenditures in the local community (within a 50 mile radius) are higher for recreation visits from non-local visitors and from those who visit the site where they were surveyed on an infrequent basis. Total estimated annual benefit of recreation use from downhill skiing is valued at $2.6 million for the LTBMU alone. Contributions to physical, mental and social well-being are not currently systematically evaluated but based on larger estimated savings in health care costs from outdoor recreation activities, the additional value is likely considerable. A Bi-State compact of the Tahoe Regional Planning Agency is focused on maintaining recreational values in the basin. A variety of stressors continue to impact the Basin including urbanization, local area use and demand, fire suppression and resulting ecosystem conditions, and climate change. These all in turn affect recreation settings and opportunities.

Sensitivity and Exposure to Climate Change

For the vast majority of activities in the region, an increase in recreation participation, with and without climate change effects, is projected. The Pacific Coast Region is viewed as the most resilient nationally to climate change effects regarding recreation use and activities. In spite of these projections, some sensitivities to climate change effects are noteworthy.

Climate change impacts are projected to continue the trend of overall increasing average temperatures, an extended warming season, and more incidences of high heat days. An extended warm season is likely to increase visitation to the basin, expanding the warm weather recreation season. A number of developed recreation settings close during the colder seasons of the year, and demand may increase for extended access to these settings, which may in turn result in extended impacts to natural systems. However, extreme elevations of temperature will likely shift the types of activities and settings visitors will seek out, moving demand closer to water bodies and well shaded areas.

While overall shifts in amount of precipitation are uncertain, extended droughts and increased intensity of rainstorms are projected from atmospheric river events. While winter demand for downhill skiing may be impacted by shifts in precipitation from snowfall to more rain, snowmaking technologies, especially at higher elevations, will preserve the majority of use, though higher costs may be involved. Cross-landscape uses such as snowmobiling, a lesser portion of the overall use in the basin, may be more affected as depth of snowpack is reduced so undesirable impacts may occur, although standards for snowpack depth are not well established. Atmospheric river events and extended drought may cause additional impacts during the rainy seasons, causing access and resource damage issues and increasing the need for maintenance and restoration.

A continuing increase in the number and intensity of wildfires in the basin and on surrounding forests is projected. More frequent and intense fires have already affected recreation and tourism access and use in the Sierras in a number of ways. Access to the basin may be affected by fires in the region. Fires situated more locally may result in closures related to safety concerns or the need for an area to recover from fire and post-fire effects. Smoke may affect viewsheds or result in warnings to locals and visitors to avoid strenuous or even outdoor activities owing to degraded air quality. Prospective visitors may shift plans as a result, by reducing the number of days, changing locations visited, or cancelling plans to visit the area.

Implication(s) of Impact(s) on the Resource

Increases overall in recreation participation add additional demand on managing agencies and natural systems. A 2015 summary of visitor surveys suggests while most recreation users are satisfied with the overall experience and a number of facets such as environmental conditions and signage, they are less satisfied with access. Increased demand may decrease overall satisfaction on this metric. Agencies will need to increase staffing, capacity, and corresponding resources while maintaining experience quality.

If the increase in warm weather season use extends across more of the year, additional days will be needed for sites and areas typically closed during cold weather season-shifting staffing and management needs for example at the lakeshore sites only open to foot traffic in the winter and closed for overnight use. Increasing use across seasons may impact natural systems requiring increasing attention to impacts and types of uses permitted seasonally.

Extreme weather events in any direction (high heat days, extensive rainfall, heavy snowfall) can all have short term impacts on access and activities available, and where resource damage occurs, may leave areas or developed settings closed for extended periods. Wildfires have similar effects, though smoke may impact recreation visits and quality across a larger area, reducing the overall economic benefits to the economies and reducing the public health contributions from outdoor recreation participation.

Infrastructure is projected to be impacted by most climate stressors, particularly more intense storms, rising temperatures, erratic weather and periods of drought, and likely increase in fires. Drainage crossing structures will be vulnerable to increased stream flows from warm storms and rain-on-snow events. More intense rains stress road surface drainage features. Less snowpack combined with saturated soils lead to early use of roads and trails, but they will likely sustain more damage. Dam management will be challenged from periodic large storm events and periods of drought. More severe fires commonly damage trail bridges, buildings, and other facilities.

Key Elements of Adaptive Capacity and Resiliency

Strategic management of recreation and tourism opportunities must be paired with management of natural systems for paired socioecological resilience. Natural systems and social systems monitoring, as well as interventions aimed at improvements, must take both into account for success. Outdoor recreation and tourism represent considerable economic, social, and public health values, thus where possible they should be persevered or enhanced. Transdisciplinary approaches will improve outcomes overall. Continued monitoring of outdoor recreationists' experiences and outcomes are essential, with particular attention to impacts of increased demand, environmental shifts, or management responses. Recommendations for the Sierra Nevada region include recognizing and addressing mismatches in scale; considering longer term risks (greater than 50 years) in addition to short-term outcomes (less than 10 years); set adaptable objectives and revisit/modify them as needed; rely on process-based indicators; integrate valuation tools, modeling, monitoring, and research; consider the integrated nature of socioecological systems; and use participatory and collaborative approaches to facilitate adaptive responses. The importance of an integrated approach strengthened through partnerships, volunteerism, and collaboration, to outdoor recreation and tourism management, and planning will increase as climate change continues to unfold.

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Lake Tahoe Basin Infrastructure Vulnerability Assessment

Date: March 29, 2019
By: Matt Antes, Chris Gillespie, Ziga Ivanic, PMP, PE, Katie Tartaglia, and Emily Barnard, Energetics
RE: Lake Tahoe Basin Climate Change Adaptation Action Portfolio – Vulnerability Assessment of Transportation, Water, Energy, and Communications Infrastructure

Vulnerability Assessment – Transportation, Water, Energy, and Communications Infrastructure

The unique geography of the Lake Tahoe Basin (Basin) figures prominently in the climate-related vulnerability of the region's critical systems and infrastructure. The mountains surrounding the Basin restrict linkages to surrounding infrastructures and communities, forcing critical connections to span long distances through potentially vulnerable terrain. These constraints reduce the redundancy of infrastructure system connections and introduce potential chokepoints to critical infrastructure outside of the Basin. Connections to the outside world provide the Basin with tourism, freight and goods, electrical power, wastewater treatment and disposal services, and communications. Additionally, the Basin's internal systems and infrastructure are interdependent, and vulnerabilities which may degrade or disrupt one service (such as electricity) can have cascading impacts which disrupt other systems (such as water delivery, communications, and transportation systems). Critically, these infrastructure systems are vulnerable to hazards associated with current and future climate change impacts.

Resource Profile – Summary of Historical and Current Resource Conditions

Transportation

Transportation in the Basin is dominated by vehicle traffic on paved roadways, and the Basin's six highways provide the only external access (other than the Lake Tahoe Airport, which is not used for major commercial service). Basin communities are mostly distributed around the shores of Lake Tahoe, so many of these communities have only an access route at either end. The highway network serve as community main streets and supports the majority of traffic, including transit system buses, freight trucks, passenger vehicles, and emergency service vehicles. The Basin is served by multiple bus systems, although most visitors enter the Basin by private vehicle. The Basin's transportation infrastructure includes a large number of non-arterial streets, rural roads, unpaved roads, and recreational trails.

Energy

The Basin imports nearly all of its energy. Long-distance electric transmission lines and natural gas pipelines provide energy for most buildings, and liquid transportation fuels are brought in by truck. The transmission lines connect Placer County communities to Truckee and also connect the Nevada portions of the Basin and South Lake Tahoe to the Carson Valley. Liberty Utilities provides electricity distribution for California communities, and NV Energy serves Nevada communities. Southwest Gas operates the natural gas pipelines that supply the Basin. A small backup power plant is located in Kings Beach but is not typically in operation.

Water

The Basin faces a unique water challenge in that it must export all wastewater—treated and untreated—from the Basin. Placer County communities pump their untreated wastewater via the Truckee River Interceptor pipeline to a wastewater treatment plant near Truckee. Other communities in the Basin treat their wastewater at one of three treatment plants located within the Basin and then export their treated wastewater outside of the Basin. The Basin's water infrastructure is owned and operated by local utilities, including the South Tahoe Public Utilities District (STPUD) in El Dorado County, Tahoe City Public Utility District (TCPUD) and North Tahoe Public Utility District (NTPUD) in Placer County, Incline Village General Improvement District (IVGID) in Washoe County, and Douglas County Sewer Improvement District No. 1 (DCSID) in Douglas County (as well as some additional smaller utilities).

Communications

The communications infrastructure in the Basin includes both wired and wireless systems. AT&T provides wire phone service and Charter Communications (Spectrum) provides cable internet. Wireless internet service is also available in parts of the Basin through Cal.net. The Basin's data networks connect to fiber-optic trunk lines outside the Basin, including Windstream lines in Carson Valley and Truckee. Wireless data is provided in the Basin by Verizon, AT&T, T-Mobile, and MetroPCS. Twenty major cellular and AM/FM radio towers are located in the Basin.

Climate Change Hazards and Infrastructure Vulnerabilities

Five key climate change hazards threaten the Basin's built infrastructure systems with damage and/or disruption.

Extreme Precipitation, Runoff, and Flooding

Projected changes in precipitation patterns for the Basin—such as an increase of both rain-on-snow events and heavy rainfall occurrences—are likely to result in larger and more frequent "extreme" flooding events (i.e., floods that meet or exceed the current 100-year flood threshold). Flooding from overflowing rivers, creeks, ravines, or lowland areas disrupts critical roadways—of which there are few alternatives for many routes in the Basin—as well as bike paths and recreation facilities. Flooding can also damage sensitive equipment located on or near ground level. Equipment such as water pumps, communications devices, or electrical switches at substations may be subject to damage from flooding. Erosion related to flooding can undermine roadbeds, scour bridges, and impact power poles, pipelines, and other physical infrastructure. One of the most significant infrastructure vulnerabilities to flooding in the Basin is the wastewater removal and treatment infrastructure in the Basin. The STPUD wastewater treatment plant is partially located in a 100-year flood zone, although, land survey data completed for this facility show facilities at the plant are above the 100-year flood elevation. Inundation here, at sewer lift stations, or elsewhere that causes wastewater to runoff into the Lake, could cause significant ecological harm. Likewise, flooding could overwhelm the Basin's existing storm water detention basins, adding large volumes of particulates and other runoff pollutants to Lake Tahoe.

Extreme Precipitation and Landslides

Landslide hazards result from a complex interaction of geology, hydrology, and ecological systems. Climate-related factors such as the projected change in soil moisture and extreme precipitation provide an indication of an important risk factor for landslide and debris flow. Landslides can severely damage infrastructure located on or below a sliding slope. Roads, pathways, power and communications lines, water storage tanks, and pipelines located in the path of a landslide risk not only cause destruction of physical infrastructure but can also lead to lengthy disruptions as tons of rock, soil, and landslide debris must be removed to restore service. The system of critical highways connecting the Basin's communities traverse high mountain passes, canyons, and cuttings alongside potentially hazardous slope zones. In areas already prone to landslide hazards (e.g., CA 89 around Emerald Bay), projected increases in the frequency and intensity of extreme precipitation events may increase the frequency of landslides disrupting and damaging infrastructure systems.

Snowpack and Avalanche

Climate models for all scenarios project a decline in the Basin's maximum snowpack, which is the main climate-related factor affecting avalanche hazard. A decline in peak snowpack indicates a likely reduction in the number, frequency, and severity of slab avalanches. However, while the number and severity of avalanches are likely to decline, visitor traffic to the Basin is projected to increase in the future, particularly during winter seasons with heavy snowfall. This could increase the number of people exposed to avalanche hazards.

Wildfire

The current wildfire threat to infrastructure varies significantly across the Basin, depending mainly on its proximity to combustible fuels. Moreover, climate change is projected to affect risk factors that both increase and decrease the wildfire hazard in the Basin. Climate models project changes to temperature and hydrology that affect the growth and accumulation of combustible vegetation. This influences projected wildfire intensity geographically within the Basin and across emissions scenario/projection timeframes. In all scenarios, increases in fire intensity (as indicated by the projected size of a potential fire were one to occur) are projected in the mountains west and south of the Lake. Because climate change can reduce wildfire risk factors such as vegetation growth and density of combustible fuels, fire intensity may increase or decrease depending on the location in the Basin. Throughout the rest of the Basin, the direction and degree of change vary across emissions scenarios and timeframes.

Due to the large-scale nature of wildfire, fires threaten broad disruption of the Basin's infrastructure systems. Wildfires can disrupt access to roads, damage or destroy electric power and communications lines, disrupt fuel delivery services, and contaminate water supply systems. In rare cases wildfires can even cause structural damage to roads, bridges, and culverts. If residents and visitors must evacuate due to fire hazard, disruptions to the transportation and communications systems may occur when they are needed most.

Temperatures

Although the primary hazardous effect of higher global temperatures in the Tahoe Basin is related to extreme precipitation and wildfire, daily temperatures can directly damage the Basin's infrastructure systems as well. Long periods of extreme temperatures can reduce the capacity of electricity transmission lines (straining systems during peak periods of demand) and can accelerate the breakdown of binders in asphalt. The intensity of heat waves is projected to increase, with greater increases in both the end-of-century timeframe and high-emissions scenario. Heat waves are not likely to be limited to Tahoe and may strain the broader regional power grid that generates and delivers electricity to the Basin. Daily freeze-thaw cycles also affect infrastructure. Days where water melts during the day but freezes again at night can allow water to infiltrate road surfaces and then cause freeze-expansion damage. Across the Basin, the annual average number of freeze-thaw cycles is projected to decline in all timeframes and scenarios. Together, projected changes to temperature indicate that the type of road maintenance necessary to keep roads passable may begin to shift away from frost damage and towards rutting and heat damage.

Other Factors Affecting Vulnerability

The Basin's built systems are undergoing constant change as older systems, much of which were constructed in the 1950s and 1960s, are maintained and improved and new systems are built. Unlike natural systems where the primary motivator of long-term change is rising temperatures and changing precipitation, human systems are changing in response to natural hazards as well as growth in tourism and changes in technology. In the Basin, population growth in the megaregion (including the Tahoe-Reno Area, San Francisco Bay Area, Central Valley, Northern Sierras Foothills and Carson Valley) present challenges to the existing infrastructure capacity and increase the criticality of infrastructure vulnerabilities to climate change hazards. As more users rely on the Basin's infrastructure systems, any disruption to those systems affects more people. Traffic in the Basin may also be accelerated by climate change, as tourists and residents alike seek cooler temperatures in the Tahoe area.

Technological changes are another human factor driving change that has the potential to affect the vulnerability of infrastructure systems, primarily by increasing the interdependence of infrastructure systems on one another. The increasing role of digital communications means that data connectivity is becoming increasingly important for transportation systems (e.g., for the Basin's intelligent transportation systems [ITS] infrastructure. The electrification of many important technologies (e.g., electric vehicles, "smart" systems in buildings) is another human factor increasing the reliance of these systems on existing infrastructure systems. Finally, infrastructure improvements—whether driven by growth or not—generally increase the interconnectedness of infrastructure systems. Overall, the growing dependency of infrastructure systems on one another increases the exposure of all infrastructure systems to climate change hazards.

Resource Sensitivity and Exposure Impacts to Climate Change

Potential impacts to the Basin's infrastructure systems/assets were modeled to assess their relative vulnerability to climate-related hazards and to identify the driving factors of those key vulnerabilities. The analysis specifically considered the location of infrastructure assets, surrounding terrain, and proximity to other geographic features likely to increase or reduce exposure and impacts from each climate-related hazard. By assessing the exposure and potential impacts of infrastructure systems, it is possible to prioritize vulnerabilities for resilience-building actions. **Table 1** provides a description of the key specific impacts.

Table 1: Summary of Key Infrastructure Vulnerabilities by System/Asset and Climate Hazard

INFRASTRUCTURE AND CLIMATE HAZARD	REASONS FOR HIGHER VULNERABILITY
Electricity Infrastructure and Wildfire	The high-voltage transmission lines and four substations in the Basin pass through, or are located in, high-fire-threat index areas. Loss of any of these assets would create outages for a large number of people and could disrupt operations, exacerbating any existing emergency wildfire situations. Climate models project the average annual acreage burned will increase about 21% Basin-wide by mid-century.
Main Roads and Landslide	About ¾ of highway segments (stretches of highway between intersections with other highways) in the Basin are exposed to potential landslide slope hazard areas. Nearly every segment carries more than 10,000 vehicles per day. Few segments have alternative routes without long detours. Peak daily precipitation, a factor in slope instability, is projected to increase ~35% Basin-wide by mid-century.

INFRASTRUCTURE AND CLIMATE HAZARD	REASONS FOR HIGHER VULNERABILITY
Main Roads and Wildfire	Nearly every highway segment in the Basin (except US 50 in South Lake Tahoe) runs through areas of elevated fire threat index. Highways in the Basin are heavily traveled (more than 10,000 vehicles daily, on average), and nearly all would require long detours if closed. The average annual acreage burned is projected to increase about 21% Basin-wide by mid-century.
Fuel Supply and Landslide	The two natural gas transmission lines delivering fuel to the north and south of the Basin are assumed to traverse potential landslide slope hazard areas (based on their known general paths). Landslides, which can rupture buried pipelines, could cause extended supply disruptions. Peak daily precipitation, a factor in slope instability, is projected to increase by an average of about 35% in the Basin.
Recreation Facilities and Wildfire	More than half of the recreation facilities in the Basin are located in moderate or higher fire-threat index areas. An estimated 40,000+ visitors are present in the Basin on an average summer day, with a significant portion of the visitors, plus local residents, using recreation facilities. Wildfire could cause widespread disruption of these popular facilities. By mid-century, the average annual acreage burned Basin-wide is projected to increase by about 21%.
Water Treatment and Flooding	Wastewater is conveyed out of the Basin via underground pipes, which could become exposed and damaged from flooding and erosion following extreme precipitation events. In addition, lift stations tend to be located in low-lying areas, with several stations in or near 100-year floodplains. Sewer systems could be inundated from storm water leaking into manholes. Peak streamflow and runoff are projected to increase by an average of about 16% for six modeled catchments in the Basin by mid-century.

INFRASTRUCTURE AND CLIMATE HAZARD	REASONS FOR HIGHER VULNERABILITY
Bike Paths and Flooding	Several bike paths that run parallel to creeks and rivers in the Basin or along the lakeshore are located in flood zones. The paved and unpaved paths and bridges can be damaged by erosion and washout during high-flow flooding events. Peak streamflow and runoff are projected to increase by an average of about 16% for six modeled catchments in the Basin by mid-century.
Electricity Infrastructure and Temperature	Electricity is delivered to the Basin via long distance transmission lines from power plants often located hundreds of miles away. Higher air temperatures in the greater Basin reduce the capacity of transmission lines, stressing the power network in the summer and increasing risk of outages. Hotter temperatures also cause greater sag in lines from thermal expansion, increasing the risk of contacting vegetation and sparking fire events. Heat waves in the greater region are projected to increase in frequency and intensity by mid-century.

Compiled by the California Tahoe Conservancy and Catalyst Environmental Solutions

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