Integrated Vulnerability Assessment of Climate Change in the Lake Tahoe Basin

2020

CALIFORNIA TAHOE CONSERVANCY

Catalyst ENVIRONMENTAL SOLUTIONS

Acknowledgements

Thank you to all those who dedicated time and resources to better understanding the implications of climate change for Lake Tahoe and its communities.

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Available online at: tahoe.ca.gov/vulnerability-assessment

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Executive Summary

Climate change is amplifying the background stressors on natural resources, infrastructure, and communities in the Lake Tahoe Basin (Basin). Land managers and policy-makers are increasing the Basin's resilience and ability to adapt. Doing this now protects people and nature, and saves money. This vulnerability assessment provides residents, visitors, businesses, and public agencies with state-of-the-art information on how patterns of temperature and precipitation will change (called "impacts"), and how these patterns will affect the things people care about (called "implications"). The common scenarios and analyses provided will help public agencies and stakeholder organizations anticipate climate change implications, and better design and maintain their future projects that improve the quality of life, land, and waters in Tahoe. This assessment is written for a technical audience, and will feed directly into a Basinwide adaptation action plan written for all audiences.

ES 1. State of the Science in the Basin

The complex relationships between resources, infrastructure, and communities means that effective adaptation must involve all these parts (or values) of a landscape. This assessment therefore integrates these three areas of analysis, creating a single reference rather than multiple separate documents. It is referred to as an "integrated vulnerability assessment" (IVA). The assessment covers not only water, wildlife, and vegetation, but also transportation, water, power, and communication infrastructure, cultural landscapes, public health and safety, recreation, and economics. A Science and Engineering Team (SET) developed the IVA by modeling future climate impacts; assessing the sensitivity of a given value to these impacts, and the capacity of that value to adapt; and exploring the implications for these values, including key connections and feedbacks between them, altogether analyzing one system that encompasses the entire Basin.

ES 2. Key Vulnerabilities and Implications

By organizing the Basin's vulnerabilities around three sub-systems—the Lake, its uplands, and its communities—this IVA provides a model for California and Nevada to create better climate adaptation plans, better target their investments, better design their policies, and improve their management outcomes. Ultimately, this systems approach to adaptation results in healthier, more resilient, and more prosperous landscapes, including the Basin's plants, animals, and people. Below is a summary of the key findings for each sub-system:

Lake Sub-System

- As a system that depends on the health and function of other physical and biological processes and resources (e.g., runoff, vegetation), Lake Tahoe has almost no ability to adapt to changes.
- Climate change will alter lake conditions and subsequently aspects of the Lake's native biodiversity. Alterations to the native biodiversity will impact how nutrients and particles delivered from the watershed are processed.
- More extreme hydrologic events, with increasing intensity of storms, rain-on-snow events and floods, along with more extended droughts, will lead to higher flow runoff events and corresponding impacts on erosion, pollutant transport, and damage to infrastructure.

Upland Sub-System

- With more intense rainfall events over shorter periods during the year, the total infiltration to groundwater storage will decrease compared with the same amount of annual precipitation spread over smaller events through the year leading to forest encroachment and loss of wetland habitat.
- Many native plant and animal species are likely to experience shifts in abundance and distribution, and some may not be able to persist in the Basin.
- The biodiversity of native plant species may decline because of reduced moisture across the range of forest types (the highest species diversity is typically found in more moist forest environments).
- As the soil moisture decreases during drought periods, vegetation will begin to change with increased tree mortality due to drought, climate-induced insects and pathogens, windthrow, and greater risk of wildfires.
- Riparian and meadow ecosystems will remain at risk of severe wildfire due to high densities of encroaching conifers.
- Without restoration, climate change is expected to continue converting meadows to upland forests.

Communities Sub-System

- Roads, bike paths, and key infrastructure will be threatened by increased risk of wildfire, flooding, erosion, and landslides.
- Recreation use will be affected by reduced snowpack and more frequent extreme weather events.
- Public health and safety will be threatened by extreme heat events and smoke from wildfires.
- Traffic in Basin will increase as visitors seek cooler temperatures in Tahoe.

ES 3. Providing a Foundation for Further Action

This IVA provides a necessary foundation for meeting California and Nevada mandates to adapt to climate change, yet by itself is insufficient. Basin partners will produce a complementary, near-term climate adaptation action plan. Partners will start from the key findings of the IVA and identify how public agencies and stakeholders in the Basin are already addressing vulnerabilities, and what additional actions they will take in the next two years. At the same time, the process of developing this IVA has highlighted that many of the issues identified are only broadly understood, and cannot be “solved” in two or three years. Partners recognize that adapting to climate change will require sustained, long-term planning and investment. This will involve additional scientific, engineering, and economic information; building consensus around priority vulnerabilities and actions; securing funding; and ongoing monitoring that feeds back into improved management. Once the near-term action plan is complete, partners will begin determining how to best develop a long-term, strategic action plan.

Introduction

The Lake Tahoe Basin (Basin) combines nationally treasured natural resources with 65,000 residents and 24 million annual visitors. The region's 501 square miles span spectacular waters, mountains, and forests, along with five counties, 20 communities and one city. This dense interweaving of people and nature makes the Basin a challenging yet promising landscape. If California and Nevada can figure out how to adapt to climate change here, arguably they can figure it out anywhere. As communities throughout California and Nevada are experiencing impacts from climate change, both states now have major mandates to mitigate and adapt.

- In California, mandates include the 2006 Global Warming Solutions Act, the 2008 Sustainable Communities Act, and Executive Order B-30-15. The California Global Warming Solutions Act of 2006 (Assembly Bill 32) requires reduction of greenhouse gas emissions by 15 percent below 1990 levels by 2020. In addition, the Sustainable Communities and Climate Protection Act of 2008 (Senate Bill (S.B.) 375) requires regional emissions reduction targets for passenger vehicles. Finally, Executive Order B-30-15 established a greenhouse gas reduction target of 40 percent below 1990 levels by 2030. The order also requires all state agencies to integrate climate change in their planning and investments.

- In Nevada, mandates include S.B. 254, Executive Order 2019-22 and S.B. 358. Senate Bill 254 requires an annual statewide greenhouse gas emissions inventory by sector, a 20-year projection of annual emissions, and the quantification of emissions reductions necessary to achieve a 28 percent reduction below 2005 levels by 2025 and a 45 percent reduction below 2005 levels by 2045. In addition, Executive Order 2019-22 directs state agencies to collaborate with partners to help implement and accelerate cutting-edge solutions to advance climate goals. The administration will identify and evaluate policies and regulatory strategies to achieve the long-term goals of greenhouse gas emissions reductions, coordinate statewide efforts, and develop a State Climate Strategy by December 1, 2020 that will include recommendations to reduce carbon pollution from relevant sectors. Finally, S.B. 358 revises the Renewable Portfolio Standard so that 50 percent of the total electricity sold in the state comes from renewable sources by 2030.

With its updated scientific information and attention to natural resources, infrastructure, and communities, this IVA provides an essential foundation for meeting these mandates.

The Basin also has plans and policies that address climate change. The Lake Tahoe Regional Plan (Regional Plan) identifies climate change as a cross-cutting driver of change and threat to Lake Tahoe. It addresses nine thresholds designed to protect environmental quality, as well as S.B. 375's mandate to coordinate transportation and land use planning, including housing, to reduce greenhouse gas emissions. Local jurisdictions with authority over land use implement the Regional Plan through area plans. The Regional Transportation Plan (RTP) is a primary mechanism for implementing the Regional Plan. The RTP provides a vision for developing, operating, and maintaining the region's transportation system, including mitigating greenhouse gas emissions associated with automobile travel; it also contains the Sustainable Communities Strategy required to fulfill S.B. 375. The Basin's Environmental Improvement Program (EIP) is also a primary mechanism for implementing the Regional Plan. Since 1997, more than 40 public and tribal agencies, along with a dozen private partners, have invested over $2 billion in more than 600 EIP restoration projects; since 2008, the EIP has encouraged all projects to consider climate change. Finally, in 2013 the Tahoe Regional Planning Agency prepared a Sustainability Action Plan that provided a toolkit of potential mitigation and adaptation actions that Basin partners could implement.

The Power of Vulnerability Assessments

A vulnerability assessment is a key tool for informing policy, planning, and management, including actions that help mitigate and adapt to climate change. An assessment provides the starting point for future adaptation planning, investment, implementation, and monitoring. A basic VA has three components:

1. Defining a species or resource's exposure to climate change,
2. Identifying the resource's sensitivity to climate change, and
3. Evaluating the resource's adaptive capacity.

The complex relationships between resources, infrastructure, and communities means that effective adaptation must involve all these parts (or values) of a landscape. People and nature cannot be easily separated at Lake Tahoe. The commitment to protecting the clarity of the Lake, protecting wildlife, and avoiding wildfires means that everything people do is linked in many ways to the surrounding environment. Conversely, the Basin's geography, geology, and ecology affect where people build roads and houses, the water they drink and air they breathe, and the open spaces where they play. In other words, people and nature combine to create a complex social-ecological system. One cannot just focus on a single element in isolation—it is tied to too many other things.

Typically, however, states allocate funding for climate change to individual agencies or departments. Even when these departments invest in the same areas, they seldom have any obligation to coordinate investments. California and Nevada often lose opportunities to create synergies and efficiencies by coordinating their programs. In turn, local jurisdictions and land managers must consult numerous analyses and assemble many different funding sources to increase their resilience to climate change and to adapt. This is difficult, time-consuming, costly, and ultimately less effective.

This assessment, by contrast, integrates multiple areas of analysis, creating a single reference—an “integrated vulnerability assessment” (IVA)—rather than multiple separate documents. The IVA combines water, wildlife, and vegetation; transportation, water, power, and communication infrastructure; and cultural landscapes, public health and safety, recreation, and economics. The project’s Science and Engineering Team (SET) developed the IVA by modeling future climate impacts; assessing the sensitivity of a given value to these impacts, and the capacity of that value to adapt; and exploring the implications for these values, including key connections and feedbacks between them.

To make the Basin’s complexity easier to understand, the analysis is organized around three sub-systems: the Lake, its uplands, and its communities. A systems-based approach to adaptation accounts for connections and tradeoffs between different values, and should result in healthier, prosperous, and more resilient landscapes. This IVA provides a model for California and Nevada to create robust climate adaptation plans, design policies, target investments, and improve management outcomes.

This IVA provides a necessary foundation for meeting California and Nevada mandates to adapt to climate change, yet by itself is insufficient. Basin partners will develop a complementary, near-term action plan. Partners will start from the key findings of the IVA, and identify how public agencies and stakeholders in the Basin are already addressing vulnerabilities, and what additional actions they will take in the next two years. At the same time, the process of developing this IVA has highlighted that many of the issues identified are only broadly understood, and cannot be “solved” in two or three years. Partners recognize that adapting to climate change will require sustained, long-term planning and investment. This will involve additional scientific, engineering, and economic information; building consensus around priority vulnerabilities and actions; securing funding; and ongoing monitoring that feeds back into improved management. Once the near-term action plan is complete, partners will begin determining how to best develop a long-term, strategic action plan.

What is Climate Change Vulnerability?

Vulnerability refers to the extent to which a natural or social system is susceptible to sustaining damage from climate change (IPCC). It is a function of three variables:

1. Exposure: how much the resource will be exposed to climate changes (e.g., will temperature increase one degree or two?)
2. Sensitivity: the degree to which a system will respond to a given change in climate, including beneficial and harmful effects, and
3. Adaptive capacity: the degree to which adjustments in practices, processes, or structures can moderate or offset the potential for damage or take advantage of opportunities created by a given change in climate, independent of management interventions.

The greater the sensitivity and the less the adaptive capacity, the more vulnerable something is to climate change.

Methodology

Developing the IVA relied primarily on the SET, a group of subject-matter experts and consultants. The SET interpreted downscaled, modeled projections of changes to temperature and precipitation patterns in the Basin (called “impacts”), prepared by the University of California, Davis (UC Davis). The SET then prepared a technical memorandum for each element of the three sub-systems that explored how these impacts would affect specific values (called “implications”). After looking at each value independently, the SET then highlighted key relationships. The team also prepared qualitative and quantitative analyses of the economic costs of these implications, noting where data was rich or poor. All technical memoranda are available on the Conservancy website at https://tahoe.ca.gov/vulnerability-assessment. Catalyst Environmental Solutions, the lead consultant, then synthesized this information and drafted the IVA. Partner agencies and stakeholders reviewed and commented on the draft, and California Tahoe Conservancy staff made final edits.

In preparing their analyses, the SET assessed the sensitivity and adaptive capacity of sub-system elements based on a combination of peer-reviewed literature, professional judgment, and peer deliberation. To compare the relative vulnerability of natural resources, the SET developed a heuristic scoring matrix (see Appendix A), shown at the beginning of each sub-system chapter. These matrices provide a general assessment of relative vulnerability, though should be interpreted with caution—they are not the result of a comprehensive, peer-reviewed, statistical analysis of published literature.

The Lake Tahoe Basin's Future Climate Conditions

The Basin is a high-elevation, geographically diverse landscape that contains a variety of ecosystems and communities. The range of elevations and microclimates means that climate change will not occur equally everywhere. This section describes modeled projections of future climate trends conditions, scaled down to the Basin, and notes areas that may undergo more or less intense change.

The IVA relies on modeled projections prepared by UC Davis for two future greenhouse gas emission scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) for use in global circulation models (GCMs). These projections are available for use by all Basin partners. Inherent in each model run are assumptions about future atmospheric carbon dioxide concentrations and their heating potential, expressed as radiative concentration pathways (RCPs). Consistent with the State of California, the IVA considers RCPs 4.5 and 8.5 to better capture uncertainty in the modeling. Under RCP 4.5, emissions rise until 2040 and then decline; this scenario considers the lower end of potential climate change. Under RCP 8.5, emissions continue through the end of the century; this scenario considers the higher end of potential climate change, and is sometimes characterized as "business as usual." Using techniques consistent with the State of California, UC Davis scaled these projections down to the extent of the Basin to better show topographical variability and smaller-scale phenomena. In cases where modeling results for RCP 4.5 and 8.5 diverged significantly, graphics in this IVA show both scenarios; otherwise, the IVA shows only one graphic. All modeled data in this document were either produced by UC Davis or Precision Water Resources Engineering, or drawn from the Sierra Nevada Regional Report (SNRR) of the State of California's Fourth Climate Assessment.

Figure 1. Key climate impact findings.

The section addresses the following variables:

- Temperature
- Precipitation
- Snowpack
- Climatic Water Deficit
- Runoff
- Wind Speed
- Kinetic Energy of Raindrops
- Wildfire
- Lake Level

The following key climate impacts are projected for the Basin:

- Both minimum and maximum daily average temperatures will continue to increase by the end of the century.
- Interannual variability in precipitation will increase, leading to more extreme droughts and storms.
- Increased temperatures will lead to reduced precipitation falling as snow and will ultimately reduce snowpack.
- Drought stress will increase significantly by the end of the century.
- The timing of peak runoff will shift one to five months earlier in the year.
- By the end of the century, the total area burned by wildfires each decade will be 61 percent larger than in the beginning of the century.
- The surface level of Lake Tahoe will be more frequently outside of the operable range of the Lake Tahoe Dam, including an increase in amount of years being above the dam's maximum legal elevation limit of 6,299.1 feet.

Temperature

Temperature is the most accurately predicted and relied upon climatic variable when considering the impacts of climate change. The average ambient temperature in the Basin has been rising over the past decade, and this trend is expected to intensify in the future. The modeling predicts that from 2010 to 2100, average annual minimum and maximum temperatures will increase by 2 to 5 degrees Celsius (approximately 3.6 to 9 degrees Fahrenheit; Figures 2 and 3). The shape of each curve indicates an accelerated warming rate from 2010 through 2100 (Schladow 2018). Warming of nighttime temperatures is also expected to increase with climate change (SNRR).

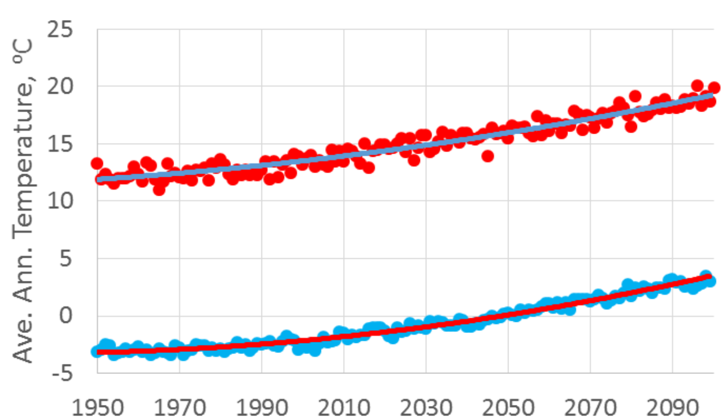


Figure 2. Historic and projected (RCP 4.5) temperature in the Basin (annual maximum daily temperatures along red line; annual minimum daily temperatures along blue line)

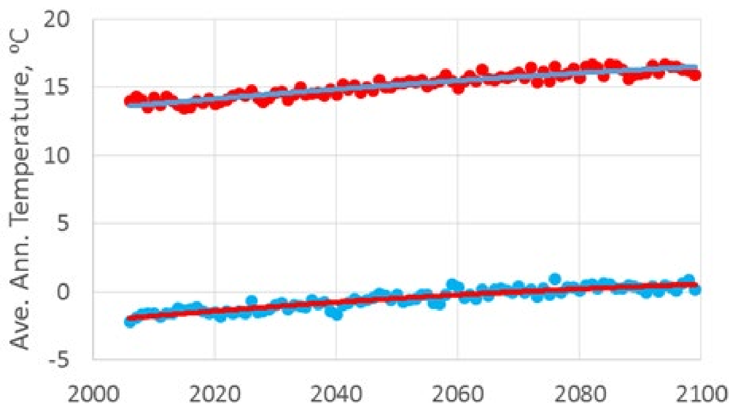


Figure 3. Historic and projected (RCP 8.5) temperature in the Basin (annual maximum daily temperatures along red line; annual minimum daily temperatures along blue line.

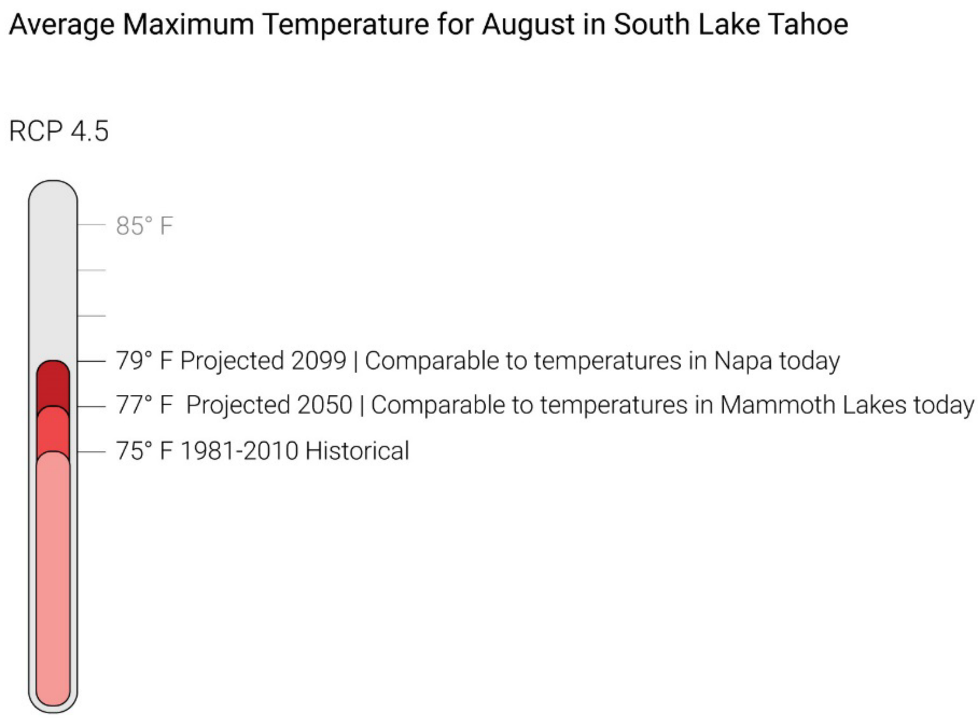


Figure 4. Future temperatures (RCP 4.5) in South Lake Tahoe will be equal to current temperatures in Carson City, Nevada and San Jose, California.

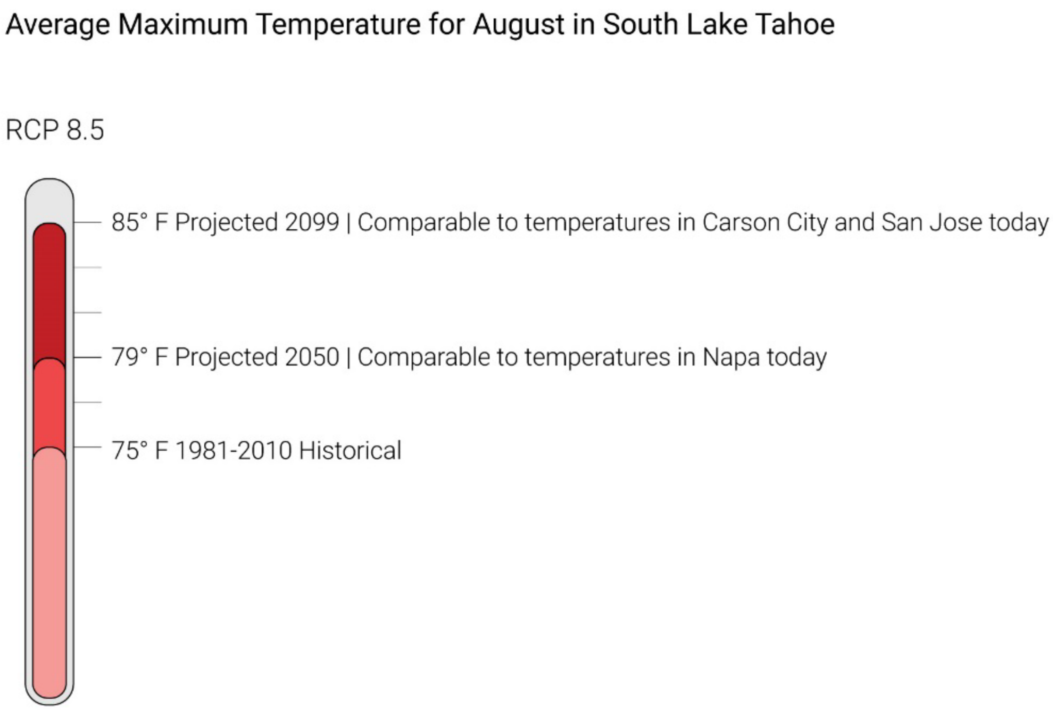


Figure 5. Future temperatures (RCP 8.5) in South Lake Tahoe will be equal to current temperatures in Mammoth Lakes and Napa, California.

Annual averages are effective in showing the overall trends, but do not reveal the seasonal and spatial changes that may occur around the Basin. Modeling of the RCP 8.5 scenario indicates that annual temperature increases are projected to be highest in the summer (0.68 degrees Celsius per decade) and lowest in the winter (0.39 degrees Celsius per decade) (Figure 6). The rate of change is consistent across the Basin, with little geographic variation detectable in the model output (Schladow 2018).

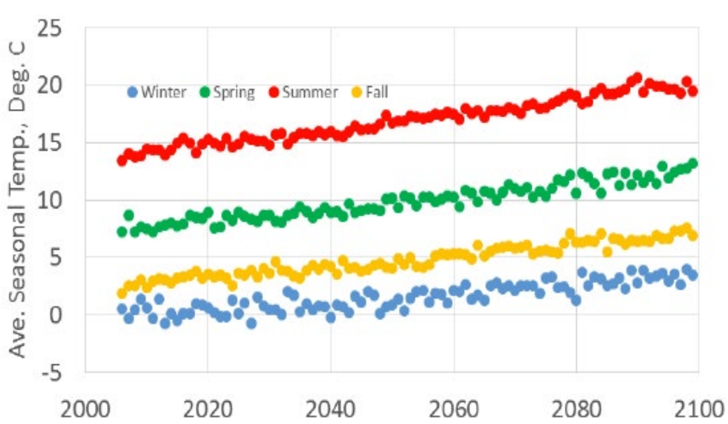


Figure 6. Average daily temperature by season in the Lake Tahoe Basin (RCP 8.5)

Precipitation

In general, projections for precipitation are less robust than for temperature, as precipitation variability tends to be extremely high between GCMs. All models show that interannual variability in precipitation will increase, leading to more extreme droughts and storms. Since 1970, a pattern of multiple-year droughts punctuated by occasional years of high to extreme precipitation has emerged in northern California and the Basin (Coats 2010). Historical observations and modeling results also show a reduced proportion of precipitation falling as snow in the Basin (see Snowpack below). As average annual temperatures rise, evaporation rates will likely increase, resulting in increased atmospheric water vapor and precipitation potential. Increased temperature can increase the water vapor carrying capacity of air: for each 1 degree Celsius increase, air can hold seven percent more water vapor. More vapor present in the atmosphere increases humidity and contributes to storm formation.

Total precipitation in the Basin is not expected to change significantly through 2100. Figure 7 compares the mean of historical precipitation (1950-2005) and the mean of projected precipitation under RCP 8.5 (2070-2099). Due to the rain-shadow effect, the western side of the Basin is expected to receive a similar amount of precipitation in the future, with the northern part of the Basin experiencing the most increase in the amount of annual precipitation.

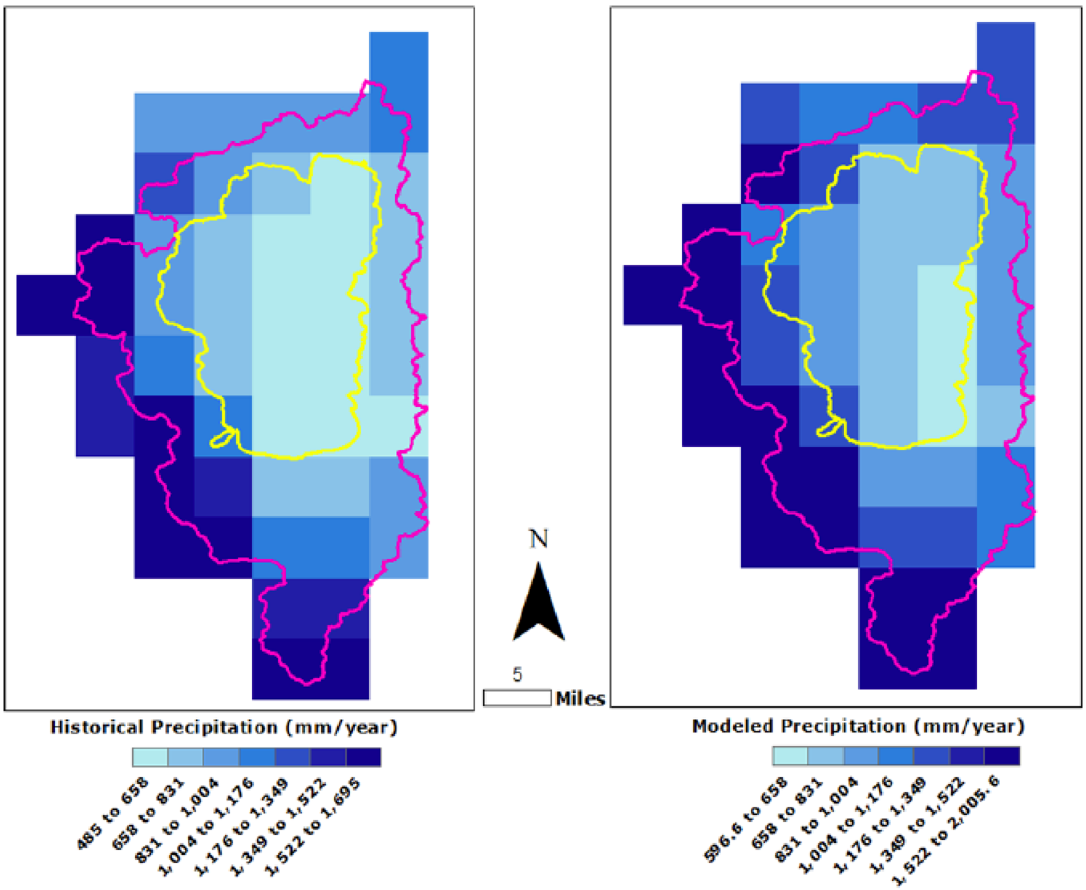


Figure 7. Comparison of mean historical precipitation (1950-2005) and modeled future precipitation under RCP 8.5 (2070-2099)

While projections of total annual precipitation do not vary considerably in the Basin, the seasonal patterns differ significantly from the historical record. For all models, the historical data exhibited maximum precipitation in winter, followed by the fall, with the minimum precipitation occurring during the summer. This pattern closely matches that of measured precipitation at the Tahoe City gage for the same period (1950-2005).

The models predict higher winter precipitation and they also predict wetter summer conditions (Figure 8). One model of the ensemble also shows a trend of significantly drier fall and spring conditions. The wetter summer pattern suggests a shift towards a more monsoonal weather pattern compared with historic conditions. Additionally, during the winter, snowstorms that quickly accumulate a large amount of snow may also increase as extreme precipitation events become more common.

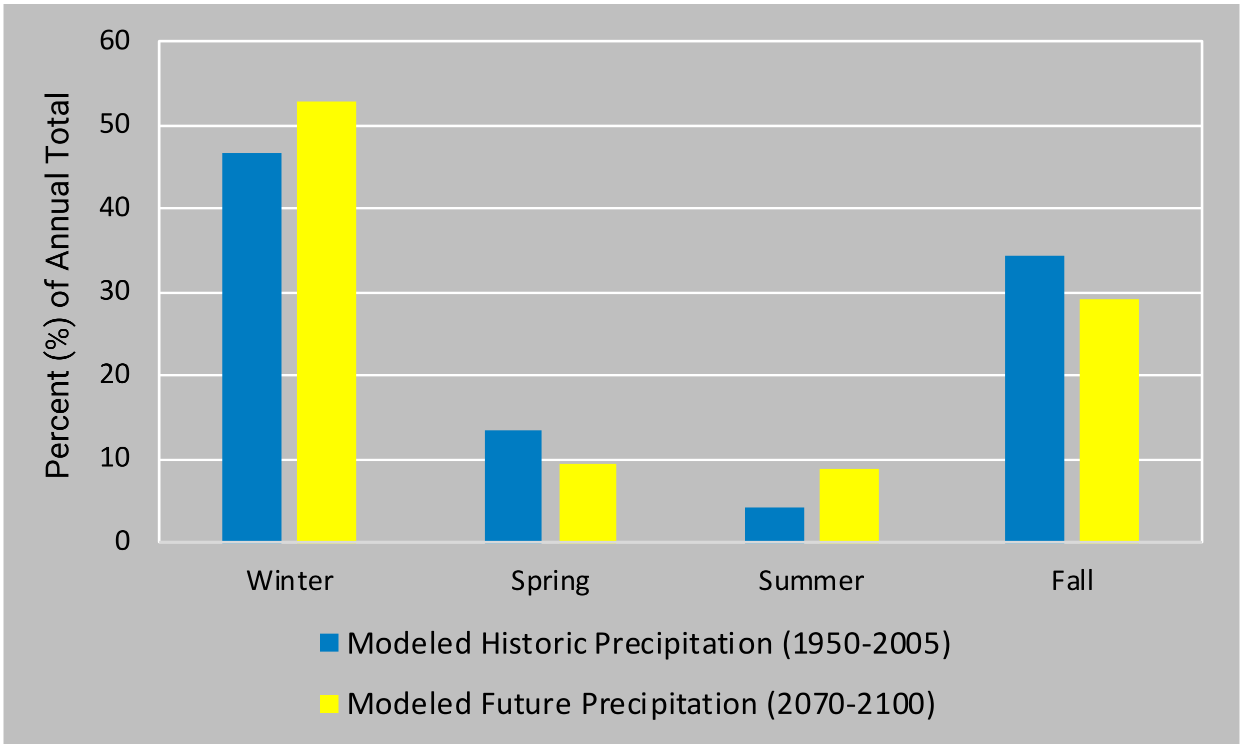


Figure 8. Modeled historic seasonal precipitation (1950-2005) and modeled future precipitation (2070-2099) (RCP 8.5) (Coats 2018)

Snowpack

Snow is integral to the Basin's water budget, ecology, economy, and recreational value, and is a major part of what makes Tahoe special. Changing atmospheric conditions threaten to shorten the duration of the winter season, and to change precipitation patterns to create rainier winters, as opposed to the historic snowy conditions.

Increased annual temperatures in the Sierra Nevada will:

- Cause snowlines to be at higher elevations (eventually above the Basin rim);
- Reduce the proportion of precipitation falling as snow versus rain;
- Cause snow to melt earlier in the spring and summer seasons;
- Lead to more rain-on-snow events (where rainfall occurs soon after snowfall); and
- Ultimately, reduce snowpack.

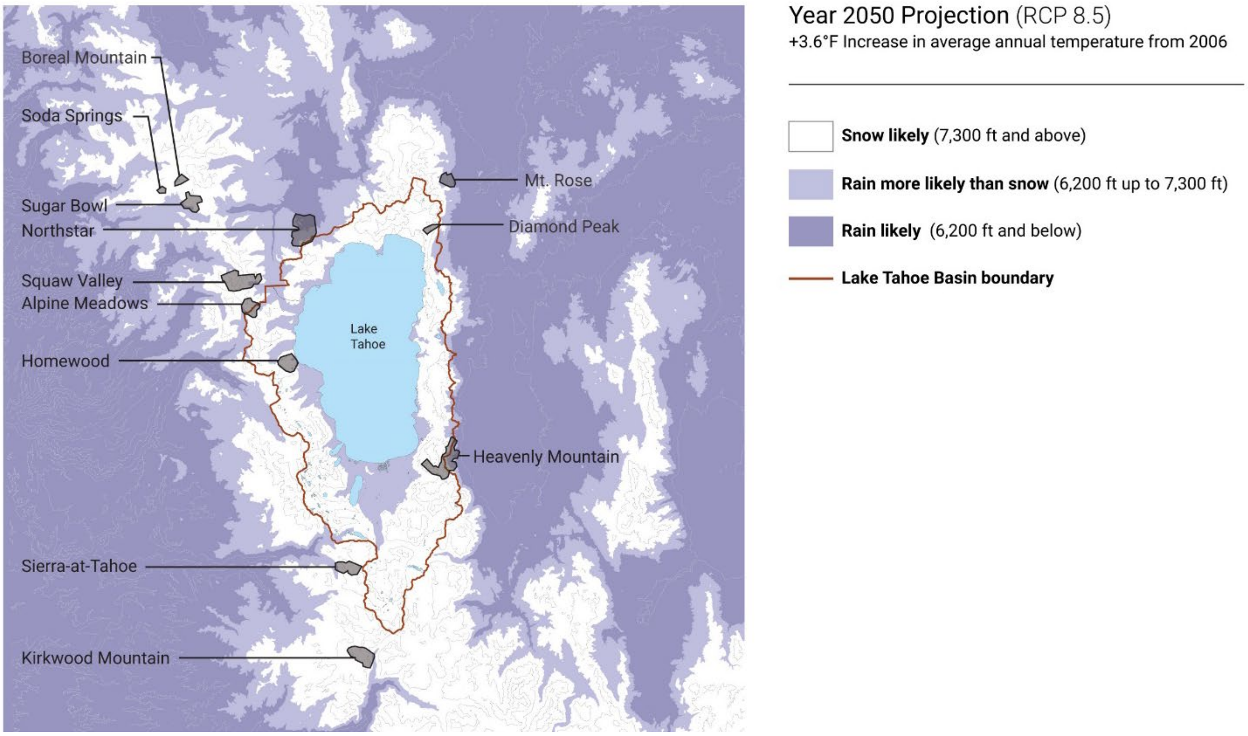


Figure 9. Increasing temperature will cause rising snowline in 2050 with RCP 8.5.

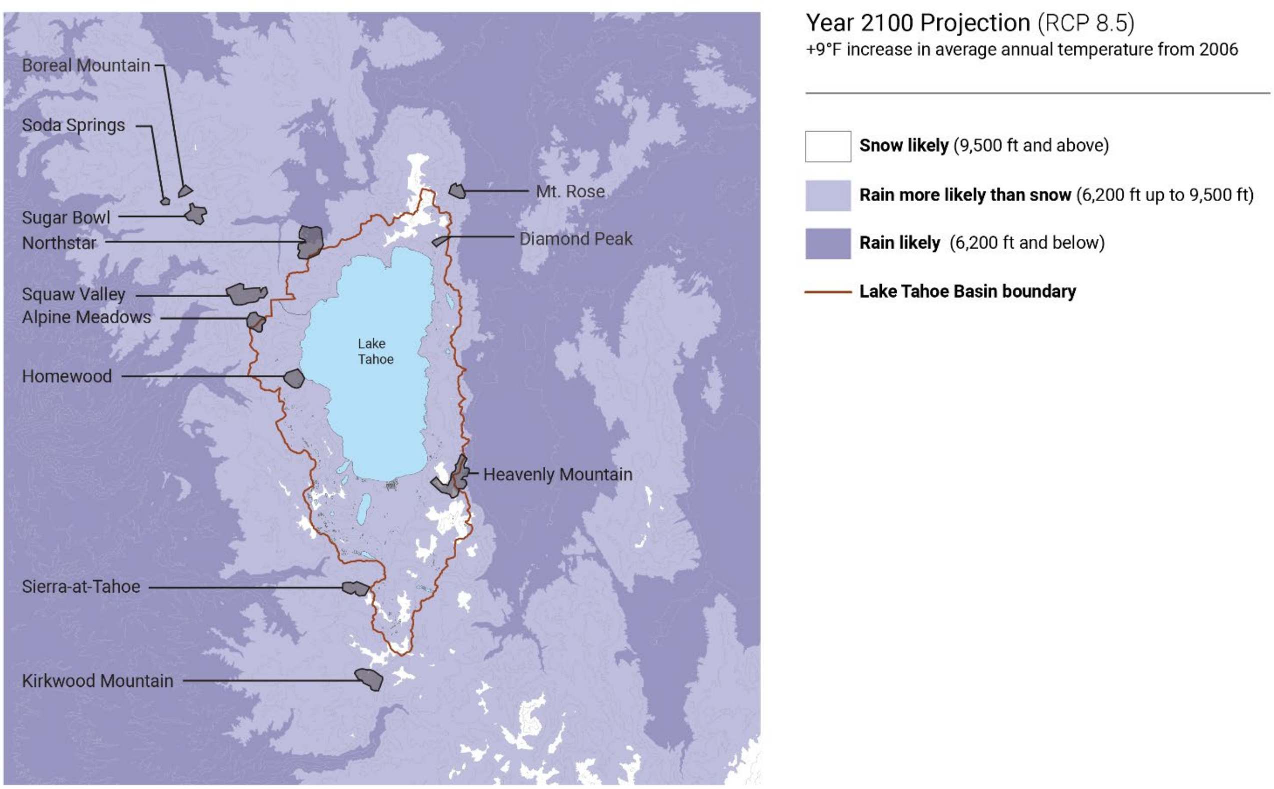


Figure 10. Increasing temperature will cause rising snowline in 2100 with RCP 8.5

While overall snowpack is likely to decrease, occurrences of extreme snowstorms and accumulations, such as record-breaking snow accumulation at some Tahoe resorts in February 2019, may also increase as extreme precipitation events become more common. Figure 11 shows the declining percent of precipitation falling as snow, averaged over the Basin. By 2100, the 5 degree Celsius increase in air temperature would correspond to a 1,000 meter (3,300 feet) increase in the snow-rain line. Thus, a storm with a snow level at the Lake under current conditions would (on average) produce rain up to an elevation of about 9,500 feet under RCP 8.5.

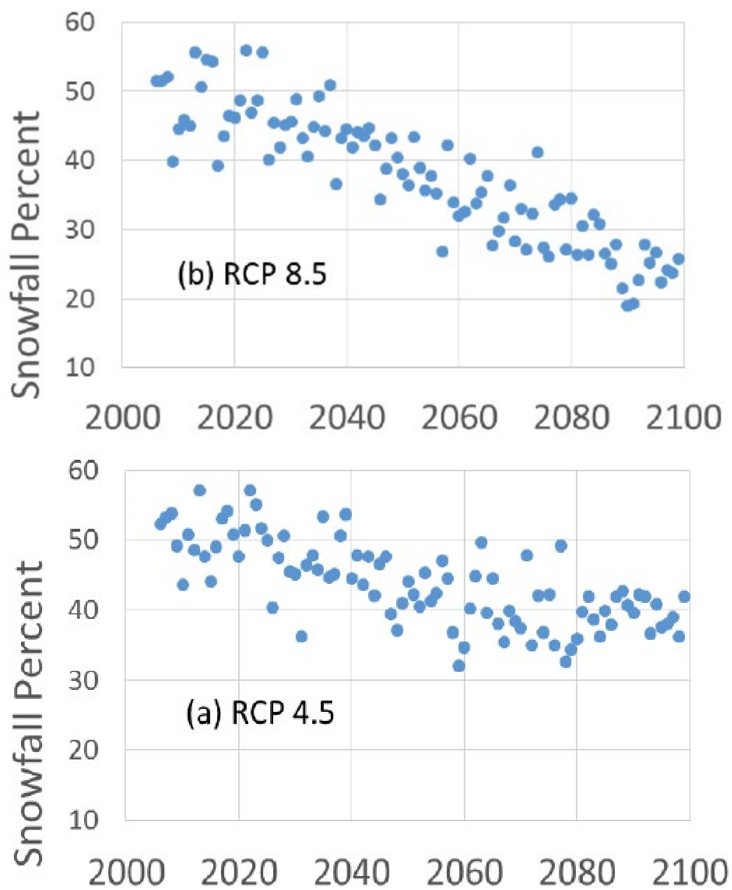


Figure 11. Projected future percent of precipitation falling as snow in the Basin (Coats 2018)

Climatic Water Deficit

Climatic Water Deficit (CWD) is the difference between potential and actual evapotranspiration (Et) and represents the potential drought stress on plants. Increased CWD is an indicator of increased drought stress, taking into account factors such as soil moisture, solar radiation, air temperature, and evapotranspiration. The RCP 4.5 and RCP 8.5 scenarios indicate CWD in the Basin will increase by 1.6 and 2 mm per year, respectively, thus indicating increased drought stress on plants in the Basin (Figure 9).

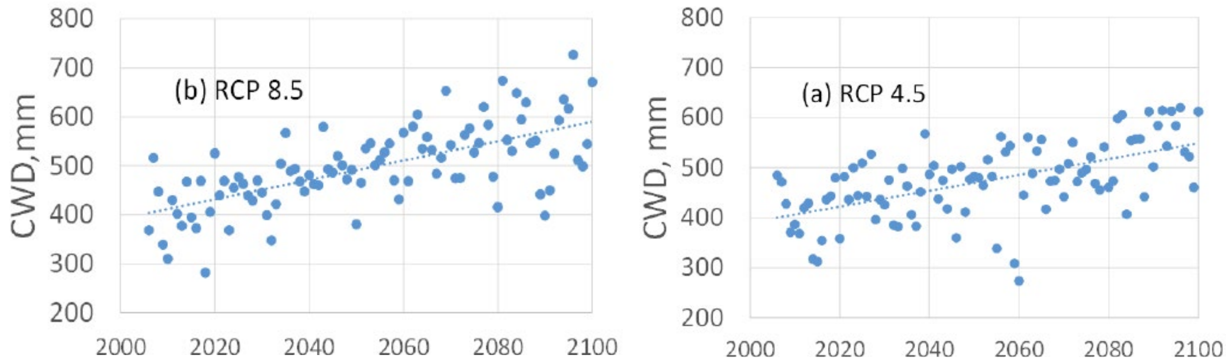


Figure 12. Modeled future climatic water deficit (CWD) (2000-2099) (Coats 2018)

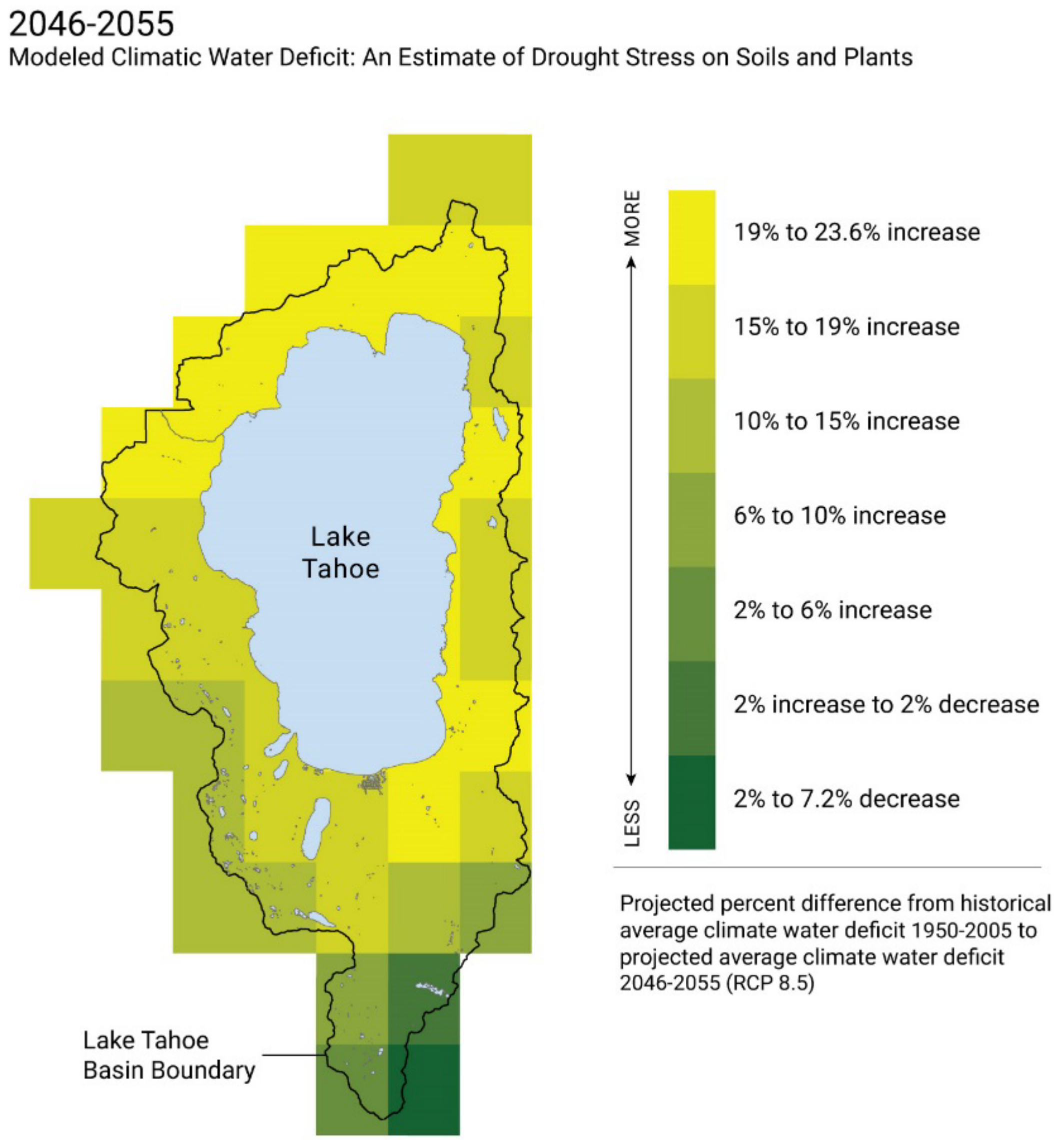


Figure 13. Modeled climatic water deficit will increase by 2055.

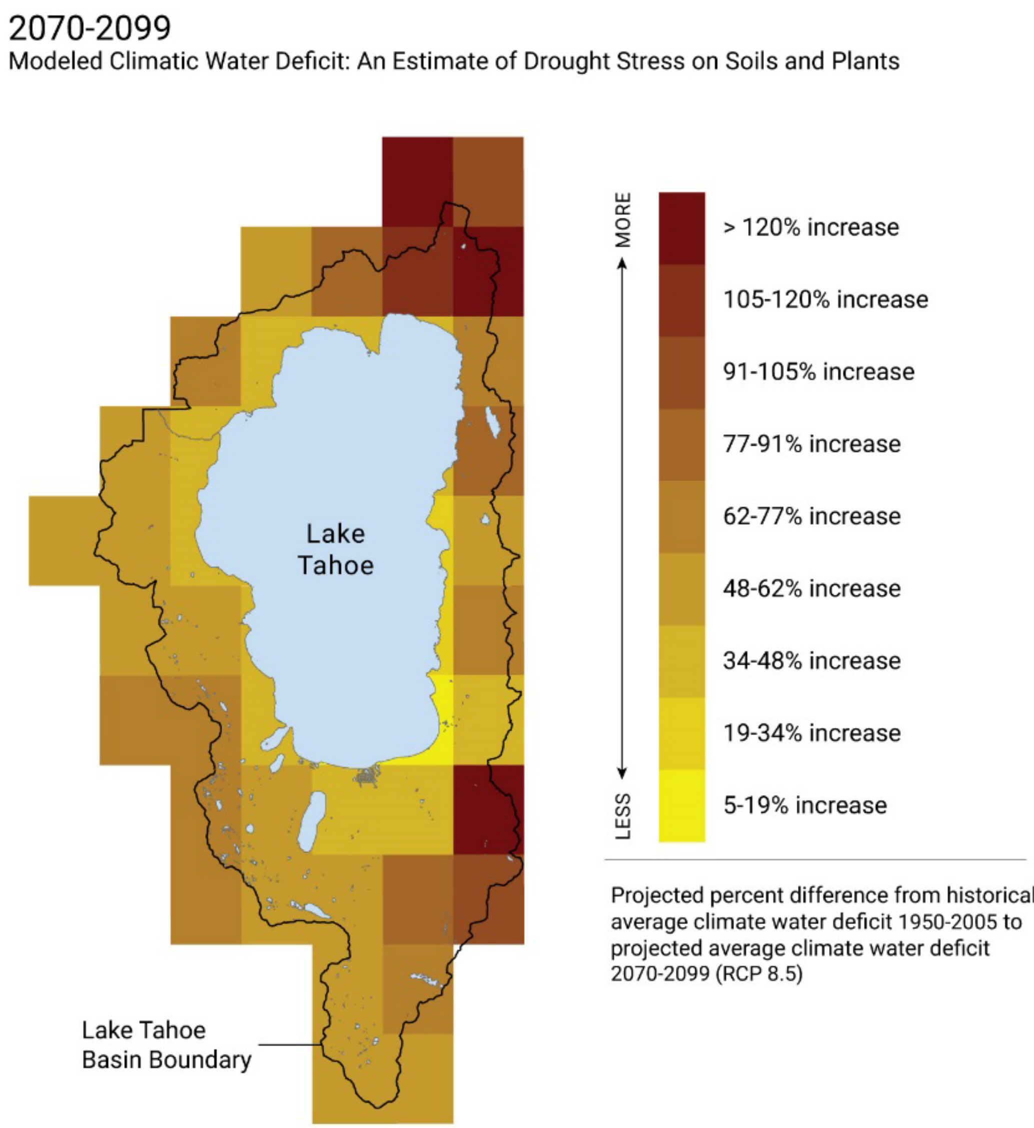


Figure 14. Modeled climatic water deficit will increase by 2099.

The model projects large and significant increases in the CWD, exceeding 120 percent in some parts of the Basin by the end of the century. The impacts, shown in Figure 15, will be most severe on the north and east sides of the Basin, where soils are of relatively poor quality and have low capacity to retain water and make it available for plant use.

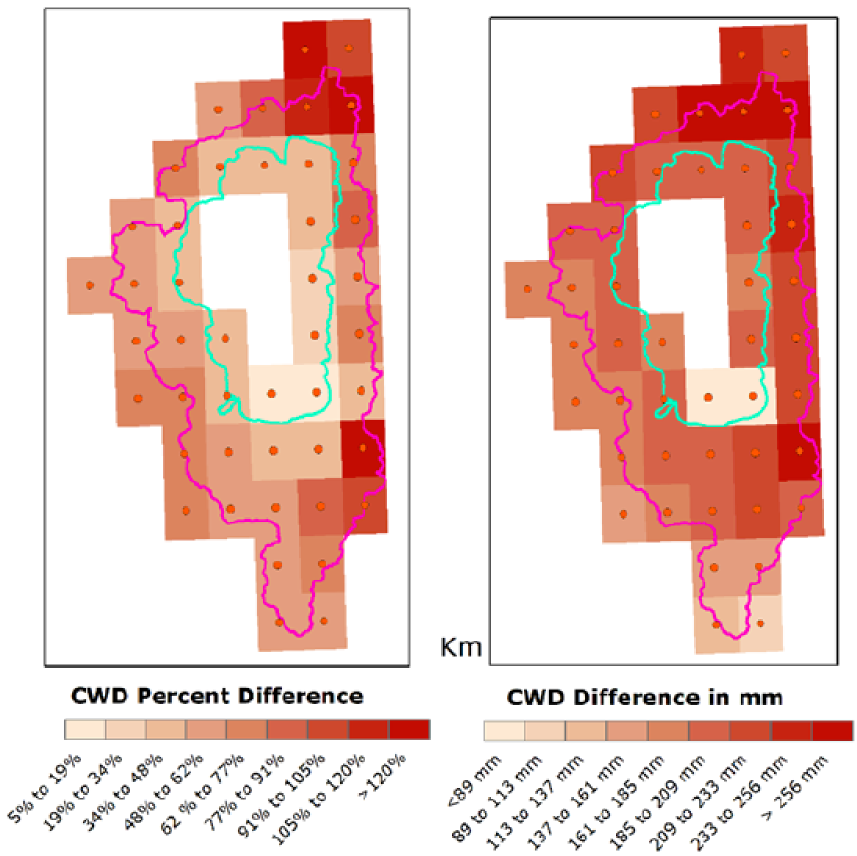


Figure 15. The geospatial change in climatic water deficit (in mm) and percent difference under RCP 8.5 (avg. 1950-2005 vs. 2070-2099)

Runoff

Modest increases in runoff in the Basin are projected under RCP 8.5, with large interannual variability (Figure 16). These increases are likely driven by the increase in precipitation.

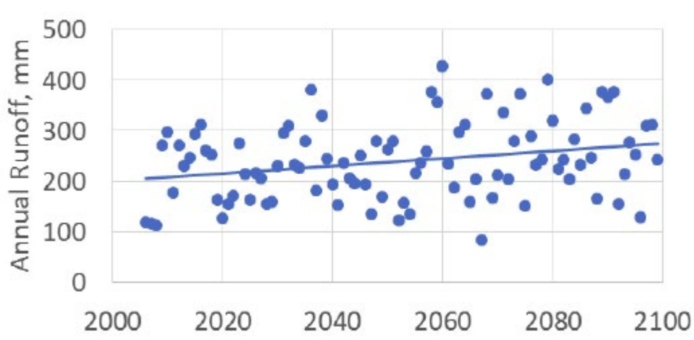


Figure 16. Projected annual runoff (RCP 8.5) (Coats 2018)

Although the total annual runoff may not change appreciably, the timing of runoff will likely change dramatically. Figures 19 and 20 shows the shift in monthly runoff from the mean of historic conditions to the mean of the modeled 2070-2099 period. Each water year begins in October. The month of maximum runoff shifts from the ninth month of the water year (June) to May and January (for RCP 4.5 and RCP 8.5, respectively). The projected temporal shifts in runoff represent changes in stream hydrology that could have significant ecological consequences.

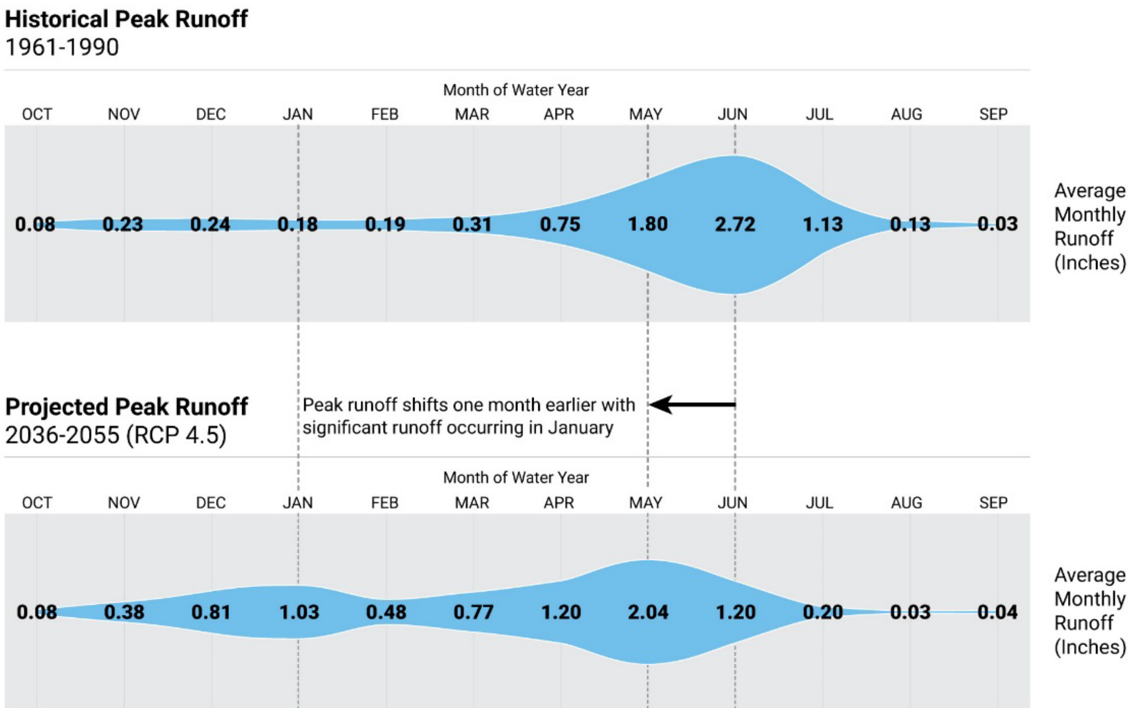


Figure 17. Peak runoff moves from occurring only in May and June to an additional, smaller peak in January by mid-century with RCP 4.5

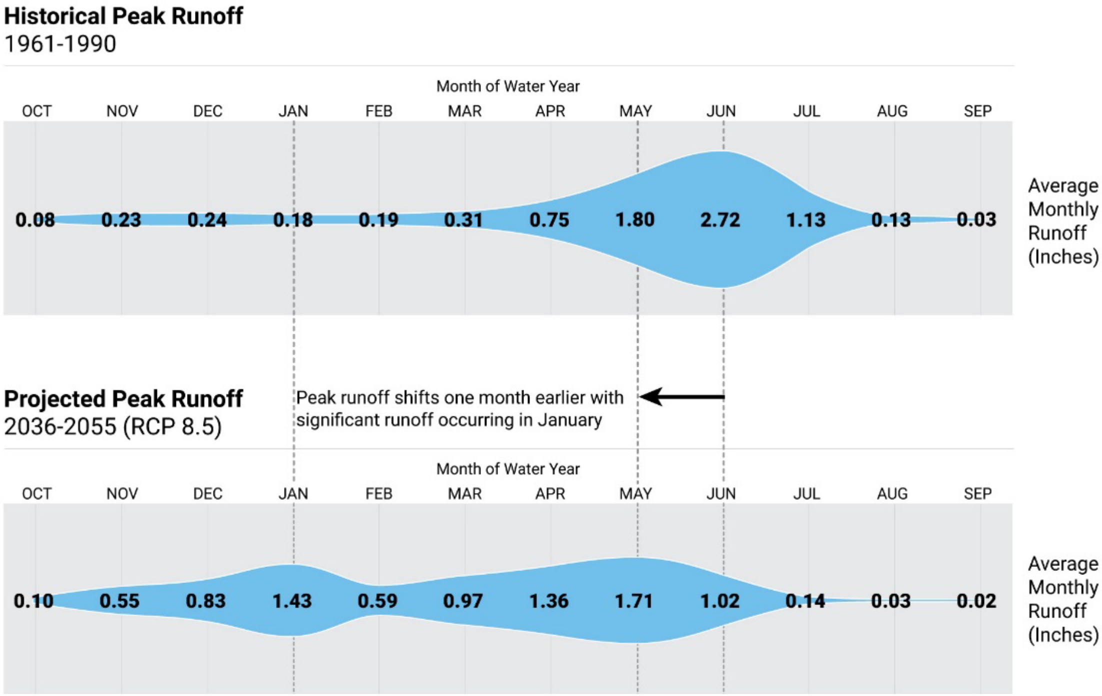


Figure 18. Peak runoff moves from occurring only in May and June to an additional, equal peak in January by mid-century with RCP 8.5

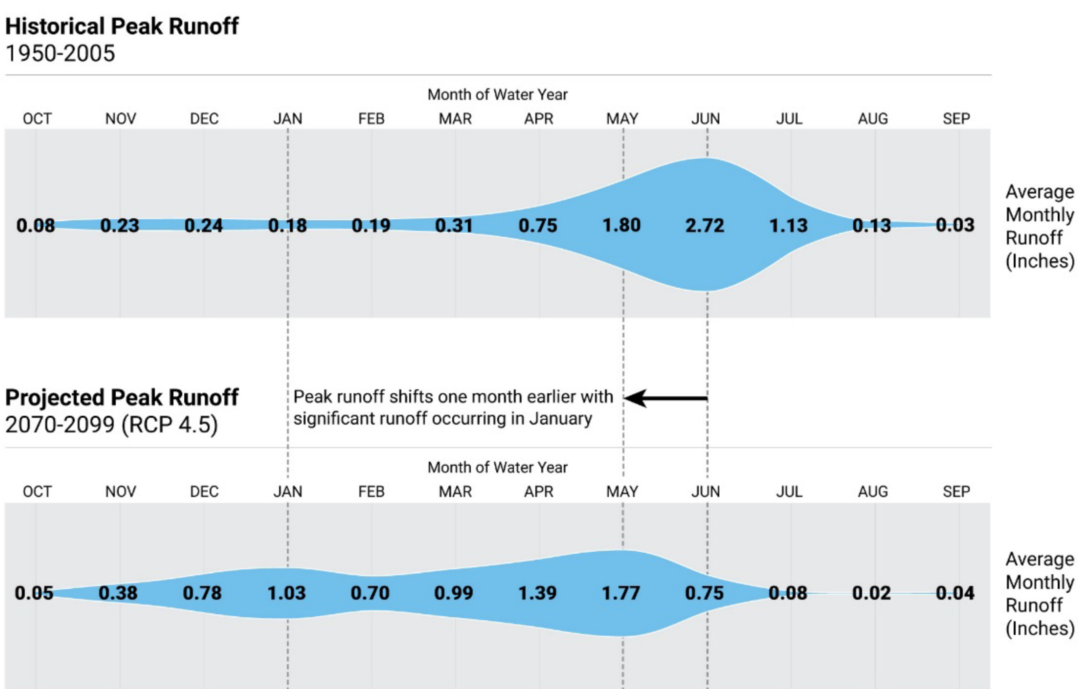


Figure 19. Peak runoff moves from occurring only in May and June to an additional, equal peak in January by late-century with RCP 4.5

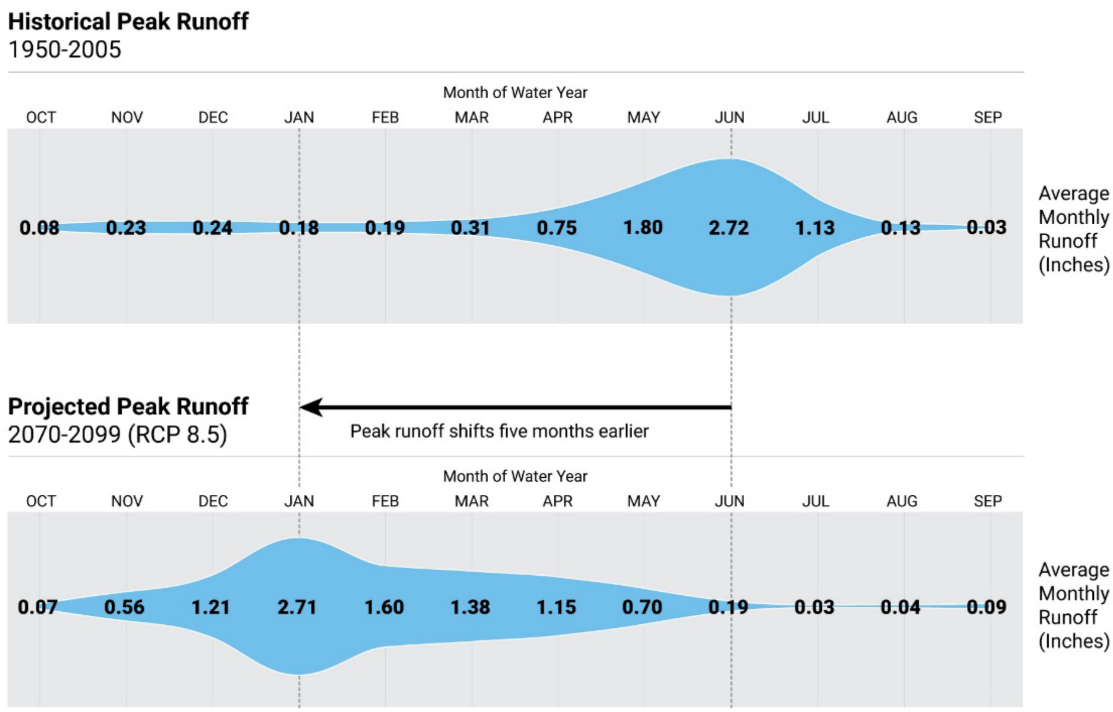


Figure 20. Peak runoff moves from occurring May and June to January by late-century with RCP 8.5 (Coats 2018)

The seasonal shift in runoff is most likely related to the shift from a snowfall to a rainfall regime, with an increase in rain-on-snow events. Figure 21 contrasts the average Basin runoff during the modeled historic month of January versus the modeled future month of January under RCP 8.5. Per the modeling, the Basin will experience a larger amount of winter runoff than occurred historically.

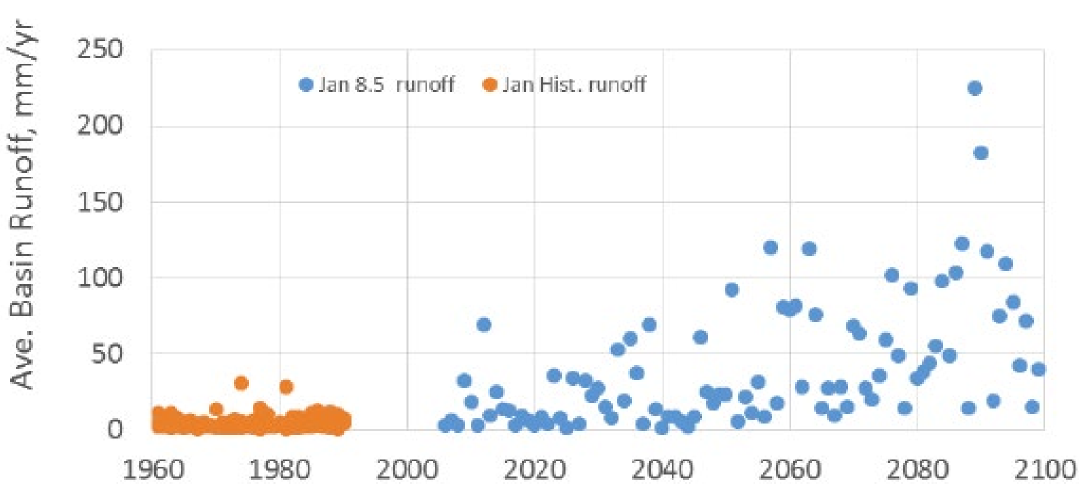
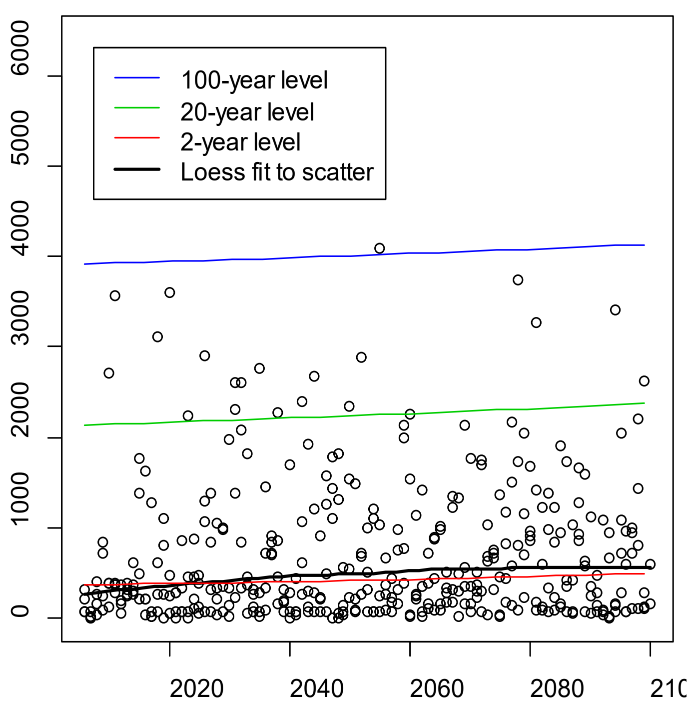


Figure 21. January runoff from 1960 – 2100 (RCP 8.5) (Coats 2018)

Based on modeling for five streams (Blackwood Creek, General Creek, Third Creek, Upper Truckee River, and Ward Creek) in the Basin, streamflow discharge is expected to climb over the next century. Although the watersheds of these six streams do not cover the entire Basin, they indicate the range of potential future streamflow changes. Figure 22 shows that the increasing discharge trend is much more prominent under RCP 8.5, with large discharge events becoming more frequent. Under RCP 8.5, maximum daily streamflow is expected to steadily increase over the following 80 years, leading to more frequent flood events. For the mid-century period, the difference in maximum daily streamflow and runoff in the Basin, compared to the baseline, ranges from -12 percent to +7 percent for RCP 4.5 and from +8 percent to +24 percent for RCP 8.5. For the end-of-century period, the change in maximum daily streamflow and runoff (compared to baseline) ranges from -8 percent to +21 percent for RCP 4.5 and +61 percent to +90 percent for RCP 8.5. The projected shift in precipitation from snow to rain, and the acceleration of snowmelt, are the primary drivers for the projected increased runoff volumes, turbidity, and flood events.

RCP 4.5



RCP 8.5

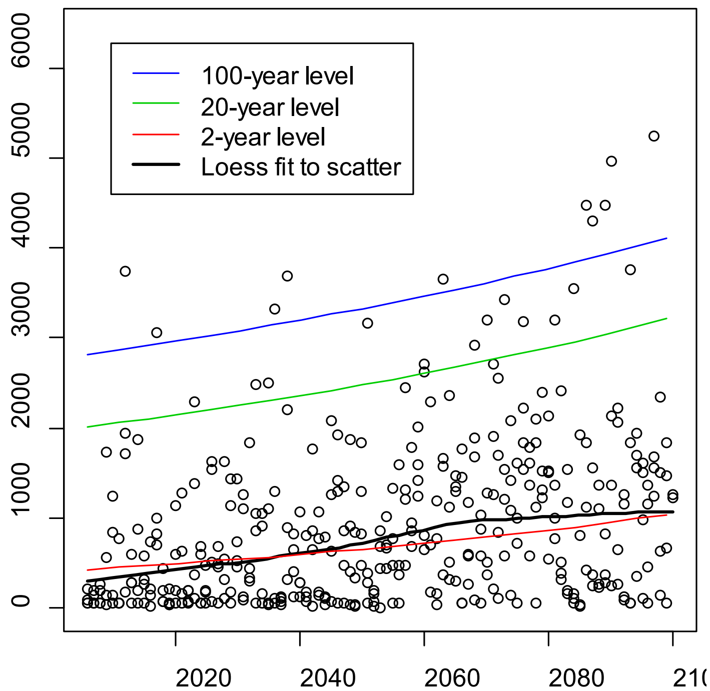


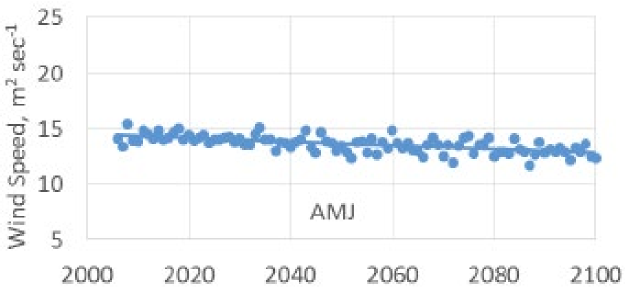
Figure 22: Projected Streamflow maximum daily discharge (cfs) for RCP 4.5 and RCP 8.5 (Coats 2018)

Wind Speed

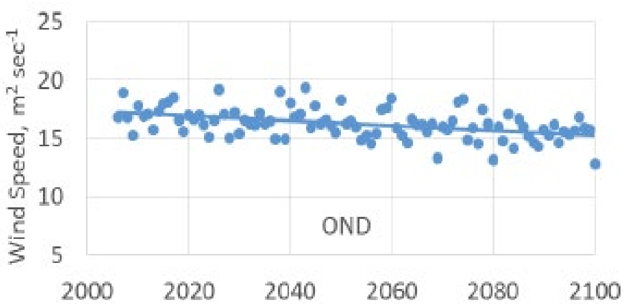
Wind contributes to evaporation, evapotranspiration, air quality, and fire behavior, and it also influences many lake processes. Therefore, altered seasonal distribution of trends in wind speed in a changing climate may be important for considering wildfire magnitude, ecological implications, and social implications.

Modeling results indicate a downward trend of the annual average of daily wind speed from 2006 to 2100, for all seasons (under RCP 8.5; Figure 23). Wind conditions under RCP 4.5 showed little to no trends. Trends in the maximum annual wind speed reflect the downward trends in the annual average. Although the magnitude of the changes is small, a decrease in windspeeds may have the benefit of reducing evapotranspiration and limiting wildfire spread. On the other hand, decreased windspeeds may also contribute to a reduction in mixing warm shallow and cool deep waters in the Lake.

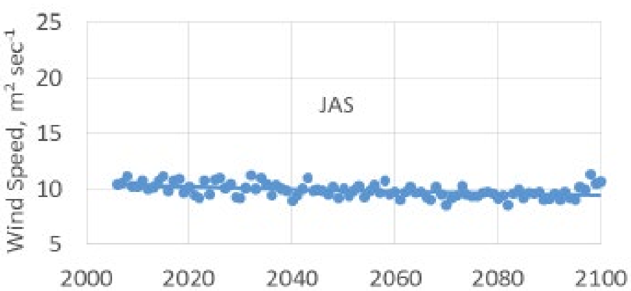
Spring



Fall



Summer



Winter

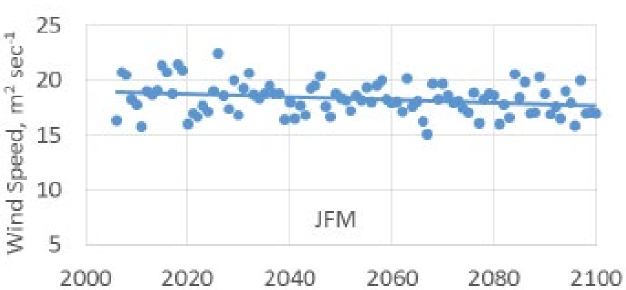


Figure 23. Seasonal trends in modeled wind speed (starting from top: spring, fall, summer, winter) with RCP 8.5

Kinetic Energy of Raindrops

The kinetic energy of rainfall is an important climate change indicator because it directly impacts soil erosion and the transport of fine sediment into Lake Tahoe. As the climate warms, the probability of intense rainfall on bare soil will increase for the following reasons:

- More precipitation will fall as rain rather than as snow;
- The protective snowpack layer will disappear earlier in the spring; and
- The frequency of intense high-energy rain events will likely increase.

In the Basin, both the maximum hourly and the total annual kinetic energy of rainfall will be affected. Modeled annual maximum hourly and annual raindrop energy on snow-free ground for a period of 1950-2100 increase under both RCP 4.5 and RCP 8.5 (Figure 24).

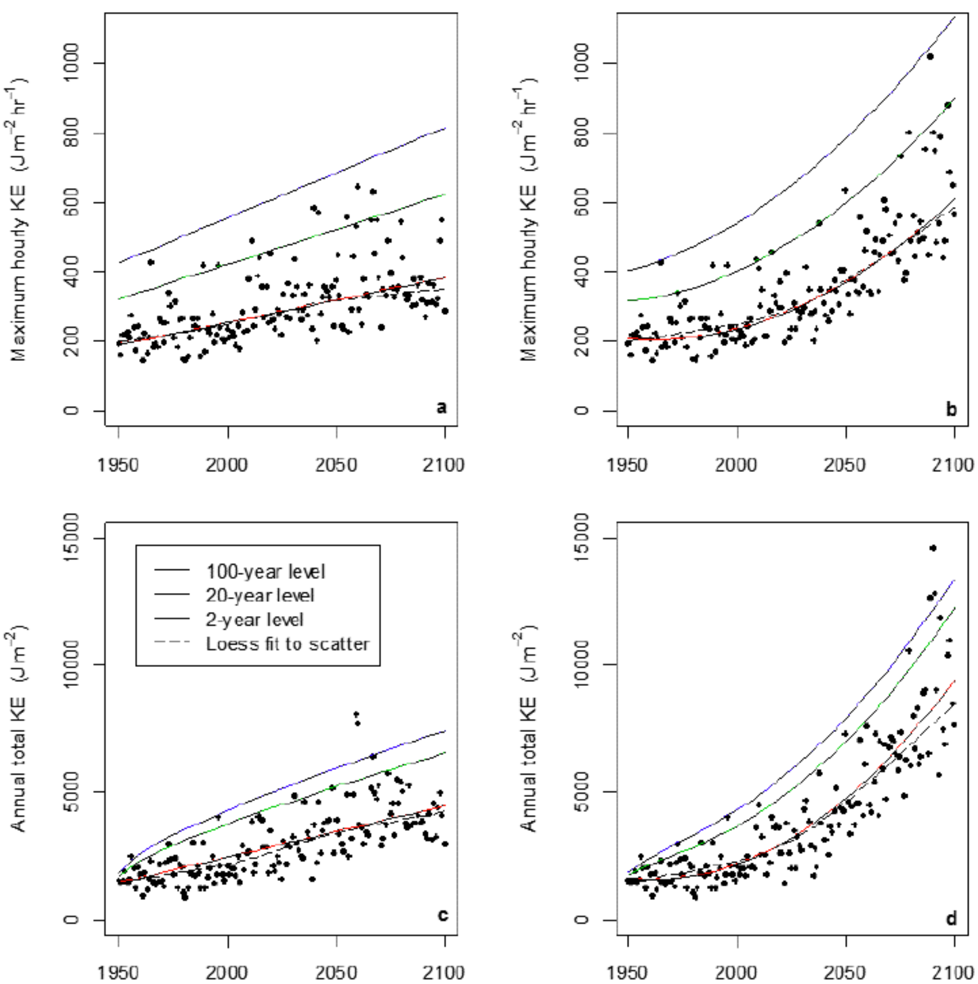


Figure 24. Annual maximum hourly (top row) and total annual (bottom row) raindrop energy on snow-free ground from 1950-2100 under RCP 4.5 (left) and RCP 8.5 (right)

Modeling results also indicate that impacts to the kinetic energy of rainfall will be greatest on the northeast and southwest sides of the Lake (Figure 25). The greatest increases in kinetic energy will be southwest of the Lake (greater than 117 percent for RCP 4.5, and greater than 269 percent for RCP 8.5).

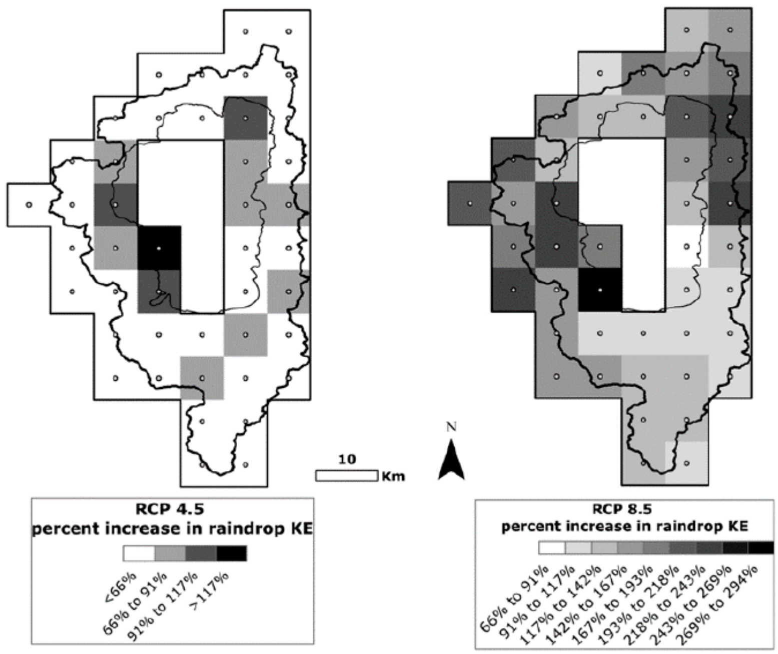


Figure 25. Percent change in average of annual maximum hourly raindrop energy on snow-free ground (J/m^2/hr) from modeled historic period to modeled 2070-2099

The projected shift in precipitation from snow to rain, acceleration of snowmelt, and increased rainfall on snow-free ground will increase soil erosion. The models indicate that loss of snow cover will have the greatest influence on the potential for increased erosion, while increased intensity of rainfall will also be a contributing factor. The increased intensity of rainfall on bare soils in the southwestern and northeastern parts of the Basin, shown in Figure 25 is important because bare soils are exceptionally erodible. While current lake clarity improvement strategies are predicated on reducing the primary contribution source of fine sediment inputs to the Lake from the adjacent small urban areas, lake clarity will also be impacted by the additional deposition of sediment from increased stream erosion (see, for example, Figure 26).

Figure 26. Stream downcutting and streambank erosion on the Upper Truckee River (USFS 2012)

Wildfire

Climate change is expected to result in significant increases in the total area of forest burned by wildfire, as well as the amount of high-severity burned forest area (Westerling et al. 2018). These predicted changes exacerbate trends in the fire regime already evident in the Sierra Nevada (Miller et al. 2009, Mallek et al. 2013, Steel et al. 2015). Regardless of the ignition source, wildfire is expected to increase in the Sierra Nevada region throughout this century (Figure 28).

Wildfires are predicted to grow in both frequency and intensity in the future due to climate change. In the Basin, the total area burned by wildfires in the end of the century (2090-2100) is predicted to be 61 percent higher than that at the beginning of the century (2010-2020). Moderate and high burn severity areas are projected to increase the most, at 89 and 80 percent, respectively (LTW, 2019).

[Figure 27 removed by the Conservancy. Direct questions to info@tahoe.ca.gov]

Figure 27. Increased wildfire expected in Lake Tahoe Basin from historic to mid-century projection to late-century projection.

The number of acres burned by wildfire in the Lake Tahoe Basin is expected to increase dramatically from the approximately 4,486 acres that burned over a recent decade (2000 to 2009; including the 3,072-acre Angora Fire). By mid-century, wildfires are expected to burn approximately 22,351 acres per decade, increasing to about 33,310 acres burned per decade by the end of the century.

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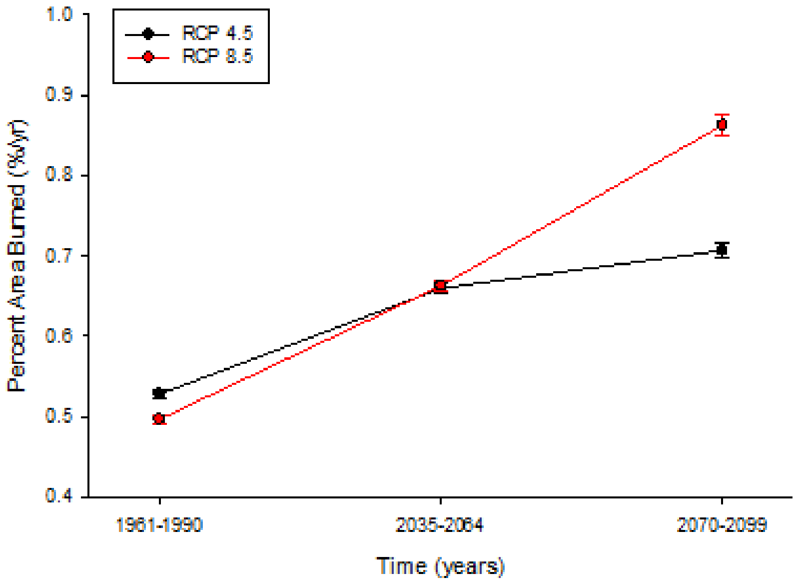
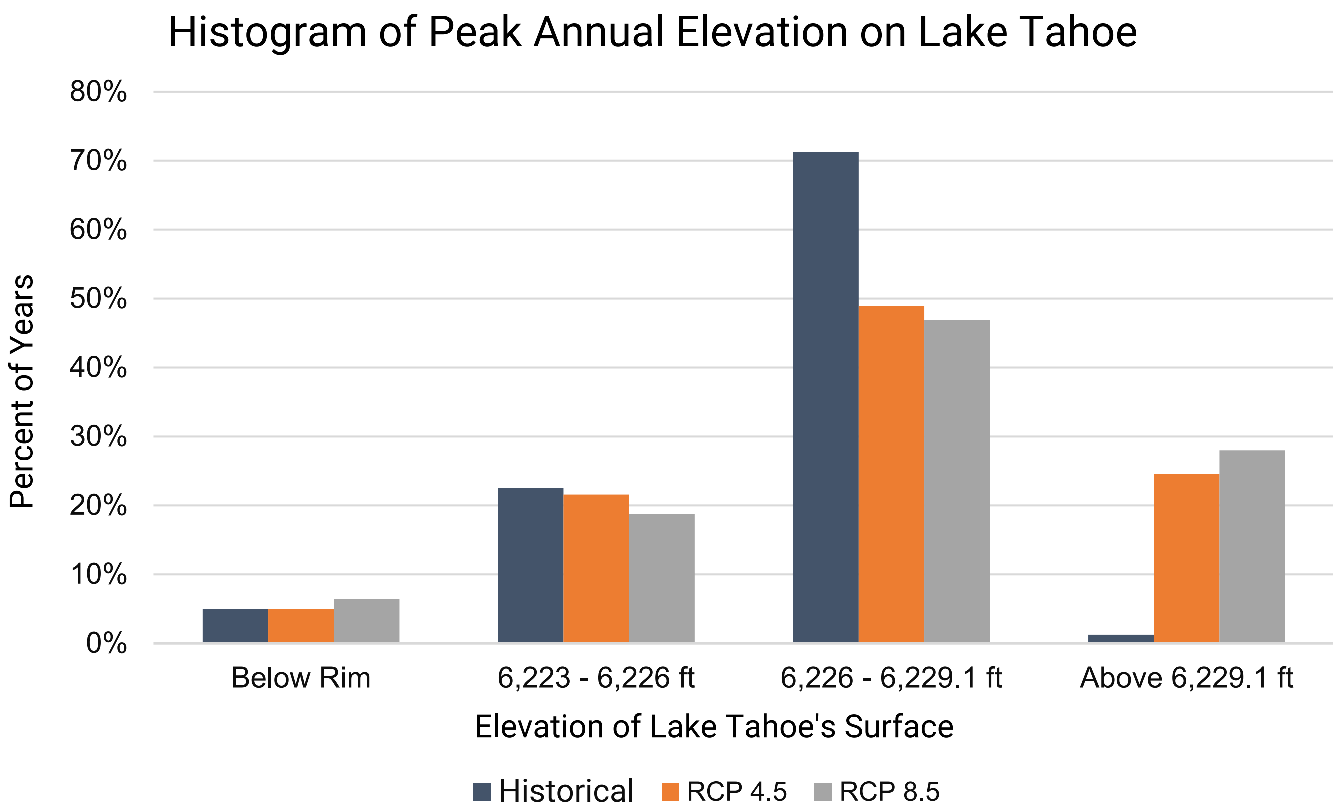


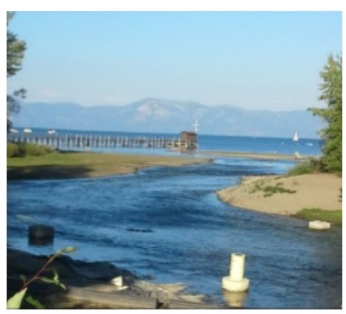
Figure 28: Projected change in wildfire for the Sierra Nevada Region, in percent of area burned per year. Boxes represent the 25th and 75th quartiles for all cells in the region with the median identified by the black horizontal line. (SNRR 2018)

Lake Level

Figure 29 summarizes the lake level modeling results. Lake Tahoe's water surface elevation typically peaks in the summer months, after the snowmelt has begun to subside and after the evaporation from the surface of the Lake overtakes the inflows to the Lake. Historically (1938-2017) the annual peak surface elevation of the Lake most often fell in the upper half of the operable range for the dam at Tahoe City (approximately 71 percent of years), and next most often in the lower half of the operable range (approximately 23 percent).



6,222.83 ft



6,223.59 ft

6,227.97 ft

Figure 29. Histogram of annual peak lake surface elevations for the historical period, and the RCP 4.5 and RCP 8.5 ensembles. Photos taken from Lake Tahoe Dam in Tahoe City, looking toward Lake Tahoe.

In both RCP 4.5 and 8.5 there is a clear shift. Generally, the results show that the surface of Lake Tahoe will more frequently be outside of the operable range of the Lake Tahoe Dam. A small increase is projected in the frequency of the annual peak elevation being below the Lake's rim, compared to a significant increase in the frequency of occurrences of the annual peak being above the maximum legal elevation limit of 6,229.1 feet. This is due to an increased frequency and magnitude of storms in the coming decades. With large inflow events, the relatively small dam at the Lake's outlet is physically unable to release water at a rate that prevents the water surface from exceeding the limit. This will result in the elevation 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 Basin; the last time Lake Tahoe was more than three-tenths of a foot over its legal limit was over a century ago.

Overview of the Lake Tahoe Sub-System's Vulnerability

Lake Tahoe is the central feature of the Basin and the terminus for most of its water resources. Climate change will stress the Lake Tahoe sub-system in numerous ways. In particular, a lack of warm shallow and cool deep-water mixing, increased invasive species and algae, and increased sedimentation will threaten its iconic water clarity and blue color. Increased visitation will also stress the Lake through overuse, habitat degradation, air pollution, and increased risk of wildfire and invasive species introductions.

The IVA analyzes the following Lake Tahoe sub-system resources:

- Lake Tahoe
- Aquatic resources
  Watershed hydrology and streamflow
- Lake-connected groundwater supply

The sub-system has the following key vulnerabilities:

- Given its dependence on the health and function of other physical and biological processes and resources (e.g., runoff, vegetation), Lake Tahoe has little to no ability to adapt to changes without management intervention.
- Climate change will alter lake conditions and hence aspects of the Lake's native biodiversity. This in turn will impact the biological absorption of nutrients and particles delivered from the watershed.
- More extreme hydrologic events (increasing intensity of storms, rain on snow events, and floods), along with more extended droughts, will lead to higher flow runoff events and corresponding impacts on erosion, pollutant transport, and damage to infrastructure.

Figure 30 shows the SET's heuristic assessment of the adaptive capacity, exposure, and sensitivity for the resources in the Lake sub-system. The SET identified the Lake itself as the most vulnerable resource in the sub-system because all resources upstream directly and indirectly impact it. On the other hand, the SET identified groundwater that is directly connected to the lake water as the least vulnerable, because the direct link modulates impacts on supply.

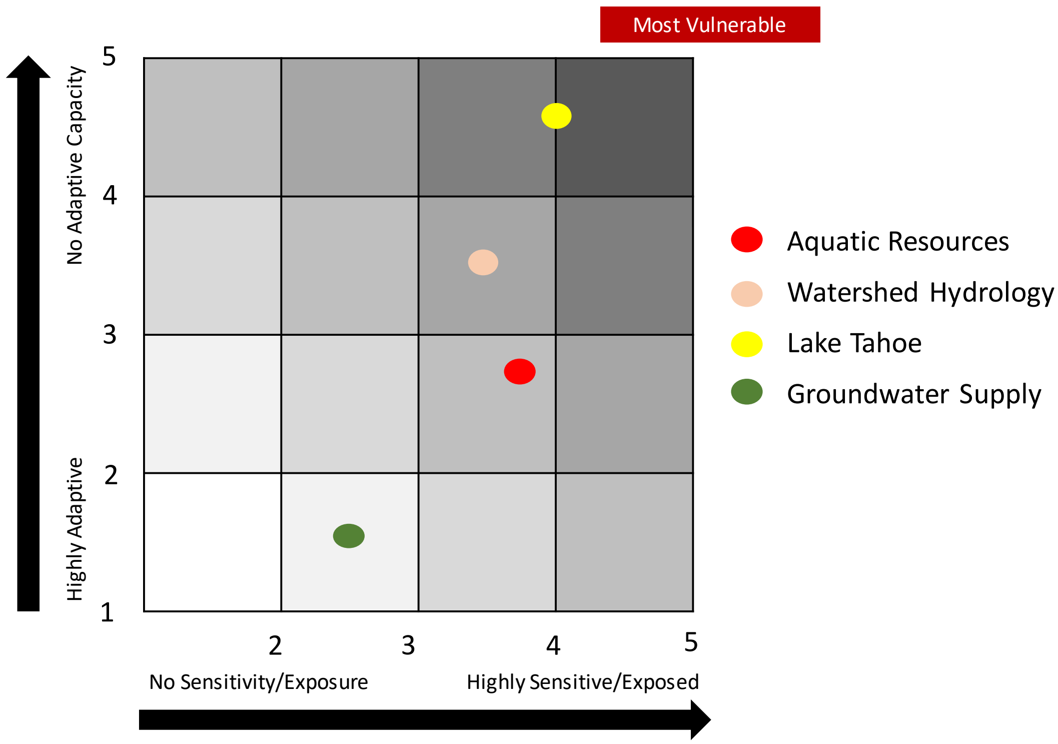


Figure 30. Vulnerability scoring matrix for the Lake Tahoe sub-system

Lake Tahoe

Historical and Current Conditions

Lake Tahoe is a unique ecosystem in the Sierra Nevada. As an ultra-oligotrophic (i.e., very low in nutrients) lake of exceptional clarity, it historically had a very simple food web that was optimized for those conditions. This historically included Lahontan cutthroat trout of exceptional size, and clear water that permitted the deep penetration of ultraviolet radiation, thus inhibiting the reproduction success of non-native fauna and flora. Changes in the lake ecosystem due to the deliberate and unintended introduction of non-native species, the decline of water clarity due to development within the Basin, and alterations of the nutrient fluxes entering the Lake have all moved the Lake away from its historical conditions.

Climate change is now impacting the Lake further and reducing those ecosystem services further, and possibly irretrievably. The presence of non-native species and land use changes can be reversed and mitigated at considerable cost, but the impacts of climate change cannot be reversed at short to medium time scales. Climate change is altering the underlying physical nature of the Lake itself.

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 degrees Celsius warmer than the previous three years. The rate of surface temperature warming between 1968 and 2017 was 0.02 degrees Celsius per year. This has increased resistance to mixing and increased the duration of thermal stratification (the separation of the Lake into distinct layers based on temperature and interaction with inflowing streams) 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 (oxygen depletion), 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.

In addition to 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 percent 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 percent of the total water supplied from all seven Truckee Basin reservoirs.

Resource Sensitivity and Exposure

Lake Tahoe has already shown itself to be highly 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). Historical and current temperatures are far lower than those expected in the next 50 to 100 years, so even larger effects are expected in the future. Given its dependence on the health and function of other processes and resources (e.g., runoff, vegetation), Lake Tahoe has little to no ability to adapt to changes without management intervention. Furthermore, the Lake currently exerts a cooling influence on the region, and this buffering of ambient terrestrial temperatures may decrease in the future. As lake temperatures increase at all depths and in all seasons, organisms that are approaching the upper limits of their heat tolerance may experience increasing stress, while organisms better suited to warmer waters may find the Lake increasingly hospitable. Warmwater non-native fishes such as bluegill and bass may be able to establish themselves further, negatively impacting native fish biodiversity (Chandra 2009).

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. Though small compared to the total volume in the Lake, this 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.

Implications

Water temperatures will continue to increase from previously recorded temperatures. More importantly, lake warming will not be uniform over its depth. The resulting increase in thermal stratification will retard the mixing that is needed for healthy lake function (see Figure 31). The wide range of consequences include:

- Inflows of stream water and urban storm water may get trapped closer to the surface, reducing clarity and adding nutrients to the euphotic zone (the zone where light levels are inadequate for photosynthesis, including the nearshore areas).
- Reduced ultraviolet light penetration may increase pathogen viability and non-native species reproduction.
- Different species of phytoplankton may come to dominate the lake flora; this trend that can already be 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 amounts of nutrients.
- Warmer temperatures, along with longer droughts and increased evaporation, may cause the surface of Lake Tahoe to go below its natural rim more frequently. This would affect how the Bureau of Reclamation manages the dam at Tahoe City for water supply to downstream communities.

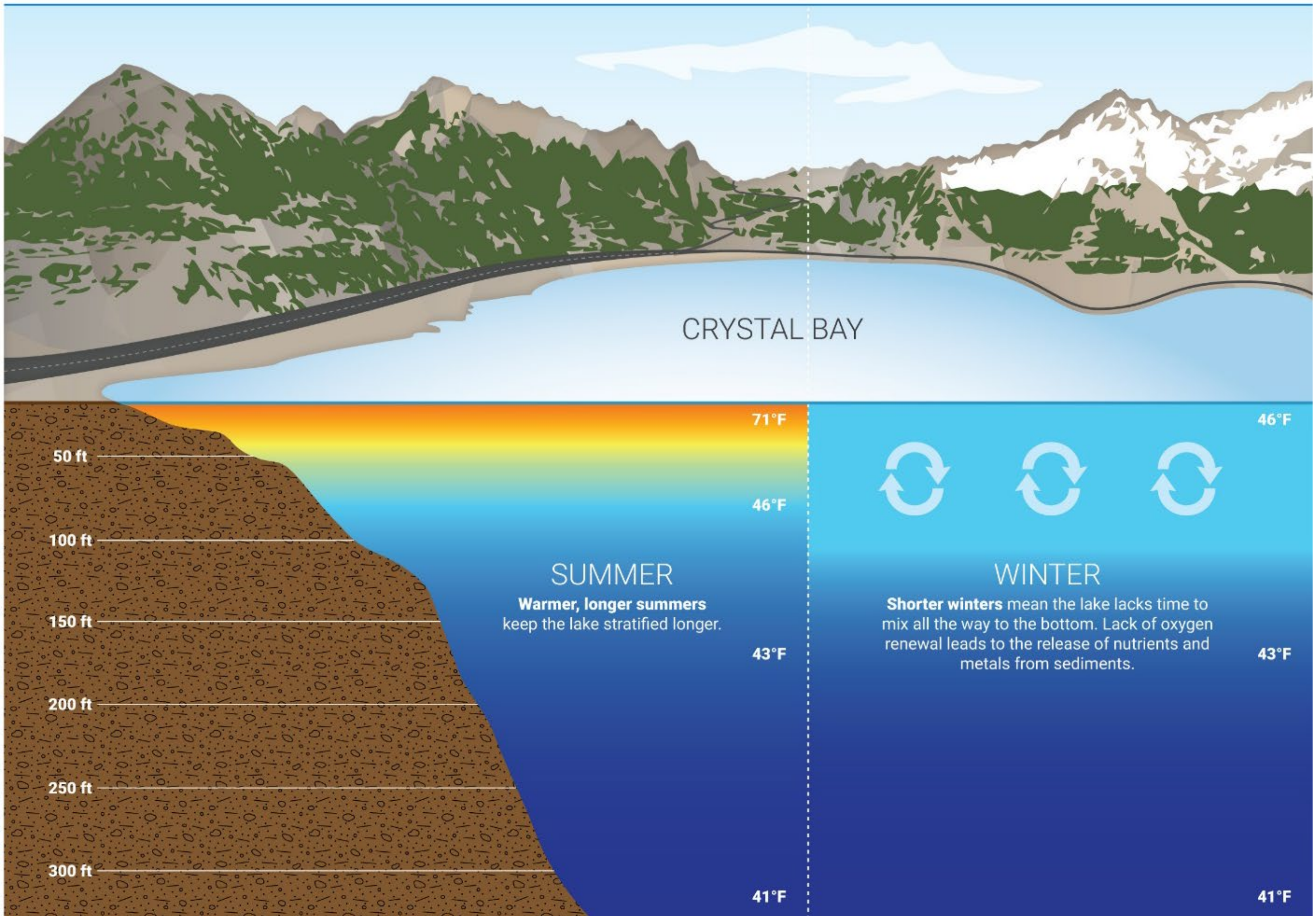


Figure 31. Diminishing lake mixing threatens lake clarity

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 dam is operated to keep the lake surface elevation below 6229.1 feet, as far as practicable, to preserve the lakeshore environment, protect lakeshore structures, and limit erosion. Figure 32 shows that the range of historical pool elevations of the Lake is relatively small and stays between these limits the majority of the time.

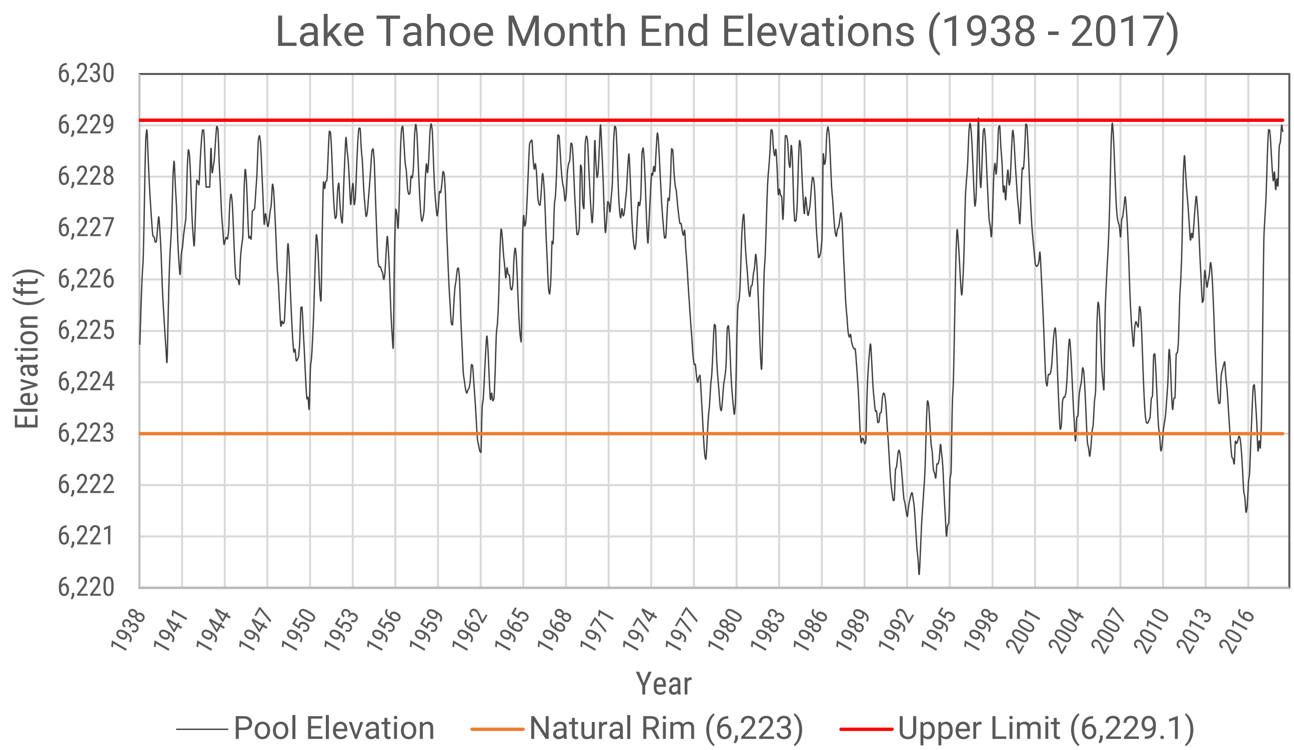


Figure 32. Historical month-end Lake Tahoe pool elevations for the years 1938 to 2018 plotted with the Natural Rim pool elevation (6,223 feet) and the legal Upper Limit pool elevation (6,229.1 feet) (Coors 2019)

Climate change is modifying the Lake's inflow volume as well as its evaporation. Increases in evaporation and decreases its inflow volume contribute to lower lake elevations, and to possible extended periods during which the surface of the Lake is below its rim, significantly impacting water supply. Conversely, decreases in evaporation and increases in inflows contribute to higher lake elevations, and more frequent exceedance of the maximum legal elevation limit. The major vulnerability is the significantly increased likelihood of Lake Tahoe's water surface rising above its legal limit uncontrollably. Modeling frequently shows lake levels up to five feet higher than in 2017 (when the Lake was at its legal limit) due to more frequent storms that overfill the Lake faster than the current dam can release water. Such lake surface levels damage lakeshore property, increase erosion, and flood areas that have not been inundated in over 100 years.

Aquatic Resources

Historical and Current Conditions

Lake Tahoe's native biological diversity historically consisted of seven fish species, 12 invertebrate orders (including at least 10 benthic invertebrate species), two to five aquatic plant species, and six zooplankton species. Native forage fish densities declined by tenfold and benthic species declined by up to 99.9 percent between the 1960s and late 1990s (Thiede 1997). Native Lahontan cutthroat trout have been extirpated in the Basin since the late 1930s. More than 16 aquatic invasive species are currently present in the Lake. Climate change may continue to alter the balance of aquatic species in the Lake, increasing non-native species density and decreasing native species density (Chandra 2009, Vander Zanden 2003).

Resource Sensitivity and Exposure

Lake Tahoe's native biodiversity may be particularly sensitive to climate change due to already reduced numbers and reduced habitat. For example, coldwater native cutthroat trout can reside in deeper lake waters but require access to streams for spawning. Climate change will alter the timing of water discharge in streams, impacting the maintenance of cooler waters within these streams from the spring into early summer periods, and the persistence of water into summer. This in turn impacts to the ability of native fish to increase their populations. Warmer winters could disrupt connectivity and the ability of cutthroat populations. This could impair efforts to reintroduce the species in the future, as well as the reproductive success of other native coldwater species.

Fluctuating lake levels due to extended droughts, and periods of rapid increases in lake level due to increased heavy precipitation events, will impact available habitat for native forage fish to spawn and rear their young. The optimal habitat in the nearshore environment is already limited. In addition, invasive warmwater fishes may also compete with and prey on native fishes may, negatively impacting native populations. Invasive warmwater bluegill, for example, compete with native fishes, and warmwater bass prey on native fishes (Kamerath et al. 2008). As temperatures in the nearshore warm or growing seasons are extended in the summer, invasive warmwater fishes may expand outward from their current occupied areas in the nearshore (e.g., Tahoe Keys) and increase their populations (Ngai et al. 2009).

Climate change may alter the balance and diversity of native and non-native species of benthic invertebrates in the Lake. Longer growing seasons can yield higher densities of invasive clam populations by increasing their reproductive output (Wittmann et al. 2013). An increased clam population can in turn alter nearshore algal communities and diversity (Wittman et al. *ibid*, Denton et al. 2012), changing the habitat for native invertebrate taxa. In addition, in lakes similar to Lake Tahoe, elevated temperatures are increasing the densities and expansion of coldwater crayfish, which feed on benthic invertebrates, macroalgae, and native fish eggs. Climate change will also impact the connectivity between aquatic ecosystems. The "wildlife connectivity" section of the Upland Sub-System further describes these implications.

Implications

Alterations to native biodiversity will impact the biological absorption of nutrients and particles delivered from the watershed. Lake mixing reintroduces particles that have settled to the lake bottom into the water column, which benthic invertebrates or zooplankton then absorb. A reduction or elimination of benthic taxa could substantially change this process. In turn, this could lead to excess particles and organic matter in the Lake, and a loss in clarity. Additionally, alterations to the fish community assemblages will change the food available for non-native sportfish. Finally, changes in the biological assemblage, and changes to the migration, movement, or mortality of species, can also alter how animals excrete and how plants release nutrients. Such nutrients control algal dynamics in the Lake.

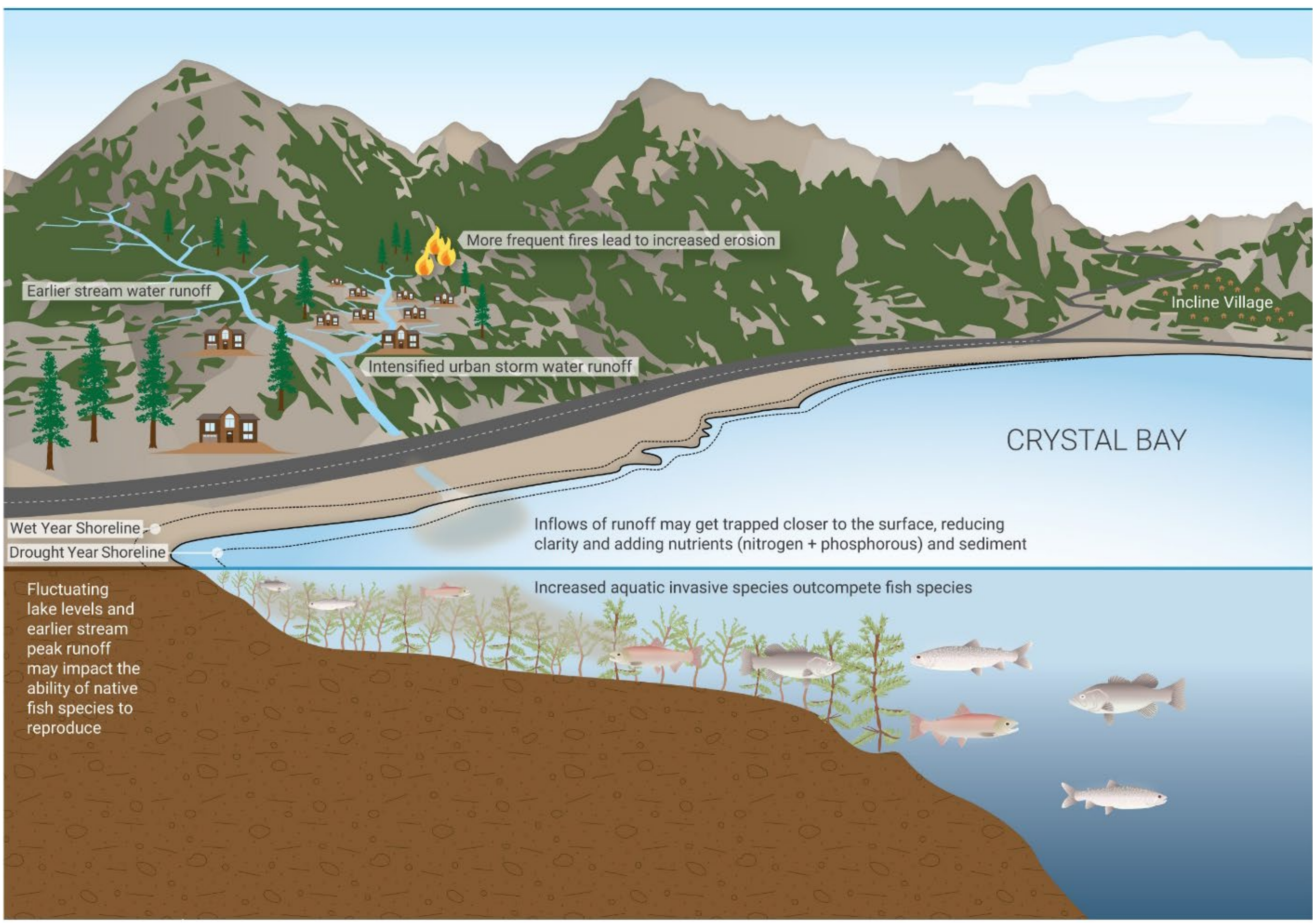


Figure 33. Multiple climate impacts degrade native fish habitats

Watershed Hydrology and Streamflow

Historical and Current Conditions

The runoff that originates from the Basin's high mountains is stored in Lake Tahoe and downstream reservoirs, and is the primary source of fresh water supply for more than 400,000 people. Historically, winter snow accumulation and spring melt have generated a significant portion of the runoff. For most of the 20th century, the Basin's water supply mostly met ecological and human demands. However, projected increased future temperatures and precipitation extremes are expected to stress the Basin.

Resource Sensitivity and Exposure

Mountain hydrology is highly sensitive to slight changes in climate, particularly temperature and precipitation. This sensitivity leads to naturally high variability in seasonal and interannual patterns of snowpack accumulation and runoff, which then affects local ecological conditions and downstream water resources. Climate change is expected to exacerbate this inherent variability, and could potentially shift hydrologic patterns across thresholds that would result in long-term changes to biological structure and function, and affect other resources that depend on current hydrology. There may be no snow below 6,000 feet and may be a significant reduction across all higher elevations. This will lead to 15 to 40 percent drier soils compared to historical norms (depending on elevation), less water for vegetation, and greater stress on plants and animals. Conversely, runoff volumes for 25-year or 100-year precipitation events will trend upward.

Stream water temperatures will also trend upward with climate change, shifting aquatic species and in-stream nutrient cycling. Dissolved oxygen concentrations decrease with increasing temperatures, so this may affect some species in riparian environments. Trends in nutrient concentrations and loading are more difficult to predict. More rain falling on exposed soils will increase mobile phosphorus and, combined with more growth of nitrogen-fixing blue-green algae, this is likely to result in more nitrogen and phosphorus in the system.

Implications

With more total annual precipitation arriving as rain rather than snow, there water that the snowpack holds will decrease, along with streamflows later in the year. This will affect ecosystems that depend on this streamflow, including riparian areas. These changes in snowpack are altitude dependent, with quicker warming trends and precipitation changes at higher elevations (Dettinger et al. 2018).

More extreme hydrologic events are predicted, with increasingly intense storms, rain-on-snow events, and floods. The precipitation from larger storms will increase by five to 30 percent, leading to higher-flow runoff events and corresponding impacts on erosion, pollutant transport, and damage to infrastructure. More intense storms and more rain-on-snow events will exceed the hydraulic capacity of existing storm water infrastructure and undermine treatment effectiveness. As a result, more sediment and nutrients would flow into Lake Tahoe. This will require engineers and floodplain managers to modify future project designs and management strategies.

Changes in precipitation and hydrology will not be uniform across the Basin, due to its complex terrain and rain-shadowing effects. The Sierra Nevada mountains typically generate more precipitation on the west shore of the Basin, and less precipitation on the east shore. Droughts are therefore likely to be more severe on the east side.

Trends in when snow melts, and the shift in peak streamflows to winter and early spring, could significantly affect downstream water supply (Barnett et al., 2005; Barnett et al., 2008). As mentioned earlier, warmer temperatures, increased evaporation, and climate variability may in turn increase the variability of water levels in the Lake, including periods below its natural rim. Again, this would affect how the Bureau of Reclamation manages the dam at Tahoe City for water supply to downstream communities.

Lake-Connected Groundwater Supply

Historical and Current Conditions

Groundwater withdrawals can draw down water tables and change the movement of water into or out of connected streams, lakes and wetlands. In turn, this can either decrease the rate at which the aquifer discharges to these surface-water features, or at which these features recharge the aquifer. Modeling for the Tahoe Valley South (TVS) groundwater basin in South Lake Tahoe has shown that north of the Lake Tahoe Airport (proximal to the Lake), most of the water withdrawal is from Lake Tahoe (Pohll et al. 2018). South of Lake Tahoe Airport (proximal to upland areas) most of the water withdrawal is from streamflow. The current groundwater extraction rates and allocations for the South Tahoe Public Utility District are well below recommended “not to exceed” thresholds, which limit pumping rates to protect stream ecology.

Similar low-elevation groundwater systems connected to the Lake are expected to be relatively resilient to changing climate, unless lake level drops precipitously. The TVS groundwater basin is expected to remain in a sustainable condition over a full range of climate projections, including RCP 8.5 (Pohll et al. 2018). Modeling shows that reductions in stream baseflows due to groundwater pumping represent only about two percent of the average annual runoff (124,000 acre-feet per year). The analysis also shows that the majority of production wells are located within areas of the Basin where groundwater pumping does not significantly impact streamflow.

Resource Sensitivity and Exposure

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

A study that modeled drought and temperature increases in the TVS groundwater basin found a 32 percent drop in recharge compared to the historical baseline, but groundwater levels only declined from zero to ten feet (Pohll et al. 2018). Similar results would be expected for other low-elevation groundwater systems connected to the Lake. Modeling shows that loss in groundwater storage and declining groundwater levels occur only under the most extreme dryer (17 percent drop in precipitation) and warmer-to-hotter (5.3 to 9.3 degrees Fahrenheit increase in temperature) conditions.

Implications

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, the desire to sustain ecological benefits would still limit extraction rates.

More intense rainfall over shorter periods during the year will reduce the amount of total infiltration to groundwater, and the associated runoff could more frequently exceed the capacity of existing storm water best management practices and infrastructure. Storm water infiltration is often advocated as a best management practice with multiple benefits resulting from reduced overland flows, groundwater recharge, and natural pollutant removal processes.

Overview of the Upland Sub-System's Vulnerability

The Basin's upland forests provide habitat for myriad plants and animals, neighborhoods for more than a dozen communities, and a recreational playground for 24 million annual visitors. Higher ambient temperatures and changing precipitation patterns are reducing the range and availability of habitat for most natural resources. The decrease in available soil moisture, loss of meadow habitat, and increase in invasive plant populations will all threaten native species. Most noticeably, people will see more frequent wildfire and smoke.

The IVA analyses the following upland sub-system resources:

- Stream-connected groundwater supply
- Forest biological diversity
- Forest ecosystem dynamics
- Soil moisture and infiltration
- Riparian and aspen ecosystems
- Meadow ecosystems
- Wildlife connectivity

The sub-system has the following key vulnerabilities:

- Larger rainfall events over shorter periods will decrease the total infiltration to groundwater, compared with the same amount of annual precipitation spread over smaller events.
- Less groundwater storage will lead to forests encroaching on meadows, and the loss of wetland habitat. In turn, high densities of encroaching conifers will increase the risk of severe wildfire in riparian areas and meadows.
- Vegetation will change due to a combination of drought, increased insect populations and pathogens, windthrow during extreme storms, and greater risk of wildfire.
- Many native plant and animal species are likely to experience shifts in abundance and distribution, and in some cases local extinction.
- Native plant biodiversity may decline because of reduced moisture in forests, especially because the highest species diversity is typically found in more moist forest environments.

Figure 34 shows the SET's heuristic assessment of the adaptive capacity, exposure, and sensitivity for the upland sub-system. The SET identified meadows as the most vulnerable resource, because changes in temperature and snowpack will decrease groundwater tables. That said, the majority of resources in this system are relatively vulnerable. The SET identified soil moisture and infiltration as the least vulnerable resource.

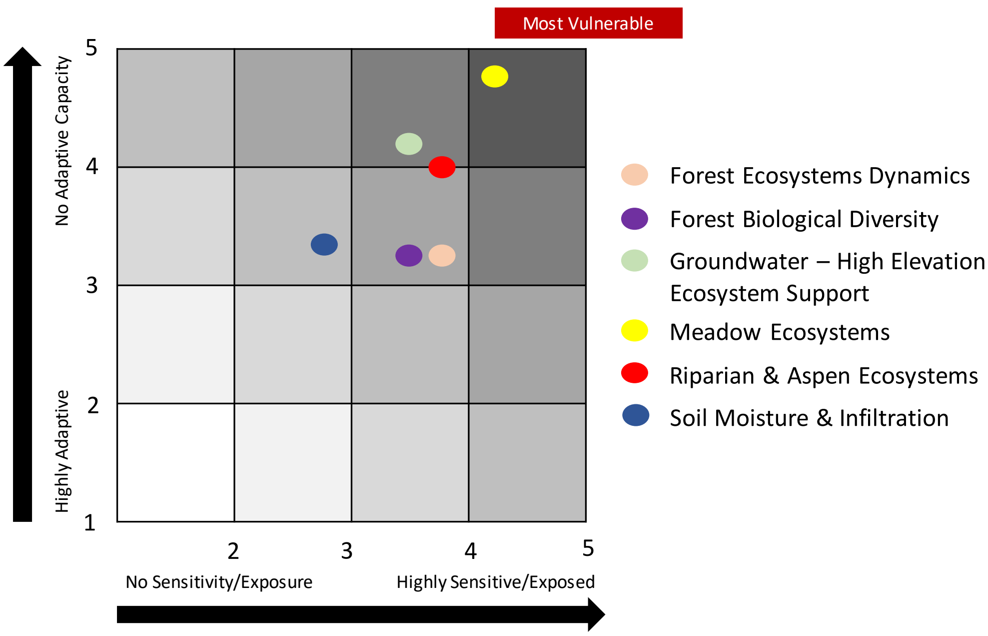


Figure 34. Vulnerability scoring matrix for the upland sub-system

Stream-Connected Groundwater Supply

Historical and Current Conditions

Snowpack and snowmelt increase the persistence of groundwater, which in turn sustains high amounts of soil moisture and a variety of high-elevation wetland environments around springs, seeps and wet meadows, especially where slope gradients are low (Rundel and Millar 2016). Reductions to the snowpack will cause groundwater levels to drop and thereby change wetland vegetation and species.

Resource Sensitivity and Exposure

It is uncertain how climate change will affect fractured bedrock aquifers, high mountain springs, mountain meadows, and headwater streams at higher elevations (Dettinger et al. 2018). The highest-elevation groundwater-dependent ecosystems (those limited to areas above 9,000 feet), may be more resilient, because snowpack will persist longer at these elevations. However, mid-elevation ecosystems will likely suffer from reduced snowpack, more frequent runoff and erosion, and dropping groundwater levels.

Groundwater systems can buffer the impacts of long- and short-term droughts. However, the relatively smaller and often isolated aquifers in mountainous parts of the Sierra Nevada are particularly vulnerable to changes in recharge and snowmelt (Dettinger et al. 2018). These impacts will vary across altitude with snowpack.

Implications

More extreme storms are expected, with an increasing frequency and intensity of the atmospheric rivers that produce heavy rain and rain on snow. Larger rainfall events over shorter periods will decrease the total infiltration to groundwater, compared with the same amount of annual precipitation spread over smaller events. Modeling of creeks in the Basin projected on average a greater than 30 percent decrease in summertime streamflows, and associated decrease in groundwater (Huntington and Niswonger 2012). The results indicate 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. Lower groundwater levels in wetland areas will allow trees to encroach on meadows and associated plant and animal habitat.

Groundwater storage in small higher-elevation aquifers can respond quickly to changes in snowfields and in local recharge rates and timing (Dettinger et al. 2018). The magnitude of precipitation is the dominant condition controlling groundwater recharge, and because precipitation in the Basin is not expected to change dramatically (plus or minus ten to 15 percent), one might assume that recharge would mimic historical patterns. This may not be the case, however, due to decreased infiltration during intense rain events, lower streamflows that drain surrounding groundwater, and longer growing seasons that increase and prolong evapotranspiration.

Forest Biological Diversity

Historical and Current Conditions

The Basin has a high diversity of species, supporting over 60 vegetation types, around 1,100 species of vascular plants, 262 birds, 66 mammals, eight reptiles, six amphibians, and 27 fish species. Timber harvest, fire suppression, livestock grazing, and urbanization greatly impacted these biological communities between 1850 and 1950. The Basin lost four bird, seven mammal, and one amphibian species, and some pine-dominant forests shifted to largely fir-dominated forests. Old growth forests declined to less than two percent of the land area, and today reside in 38 small relict stands.

Since 1950, Basin land managers have worked to restore watershed and forest conditions. They curtailed grazing and made forest regeneration a primary objective. Today, land managers regulate and seek to minimize stressors like urbanization and recreational activities, and to allow fire back on the landscape. Forest management strategies are evolving and trending toward more compatible approaches, including ecologically beneficial fire, that promote landscape heterogeneity and the retention and recruitment of older, larger trees.

Resource Sensitivity and Exposure

The Basin has a large elevation range, rising more than 4,000 feet from Lake Tahoe to the surrounding crests. Climate change has the potential to directly alter the distributions and interactions of many species. Habitat specialists and high-elevation species are most at risk. For example, the pika no longer inhabits most of its former range (high elevation talus fields). 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 alter forested landscapes and habitat conditions for plants and animals.

Implications

Many native species, including Tahoe Yellow Cress (a plant) as well as osprey and bald eagles, are likely to shift their abundance and distribution. Some may go locally extinct. Re-surveys for vertebrates on the west slope of the Sierra Nevada, conducted roughly 100 years after original surveys, found the following:

- the elevation limits of the geographic range of species shifted primarily upward;
- even closely related species responded differently to changes in climate and vegetation;
- many species showed no change in their elevational range;
- the ranges of several high-elevation species (e.g., alpine chipmunk) contracted because the lower limit moved upslope, while the ranges of several low-elevation species increased concurrently;
- 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 historical logging, fire suppression, and other land use change; and

- elevational range shifts resulted in minor changes in species richness and composition at varying spatial scales.

Invasive non-native species and lower-elevation native species that did not historically occupy the Basin could also increase in number and extent, and stress native species through competition and predation. Terrestrial non-native invasive plants (e.g., cheatgrass) and non-native animal species (e.g., barred owls) already threaten native species.

Forest Ecosystem Dynamics

Historical and Current Conditions

Historical logging, fire suppression, grazing, and invasive species introductions, along with climate change, have altered the structure and functioning of forest ecosystems. Biotic disturbances (e.g., insects, pathogens, invasive species) and abiotic disturbances (e.g., fire, drought, air pollution) interact with biogeochemical cycles and energy flows. These interactions have the potential to initiate novel successional trajectories across living (e.g., plants, animals, microbes) and nonliving (e.g., air, water, mineral soil) system components, and compromise ecosystem resilience.

Fire and drought are projected to become more severe and widespread in the future. 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

Forest growth is a critical and major carbon sink in the northern hemisphere that has the potential to help mitigate the ongoing rise in global atmospheric carbon dioxide. Predicting forest sensitivity 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 important to maximize the ability of forests to sequester carbon.

Implications

Climate change may compromise vital forest ecosystem functions and processes. For example, drought stress and widespread outbreaks by bark beetles will kill more trees. Increased mortality and larger amounts of dead wood indicate 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. Reduced moisture across forest types and aspects may decrease the diversity of native plant species, given that high species diversity is typically found in moist forest environments. However, forests and soils have the capacity to reduce localized impacts of climate change, if managed carefully. In some areas, small topographic differences can mitigate broad-scale impacts and create "climate refugia" for species.

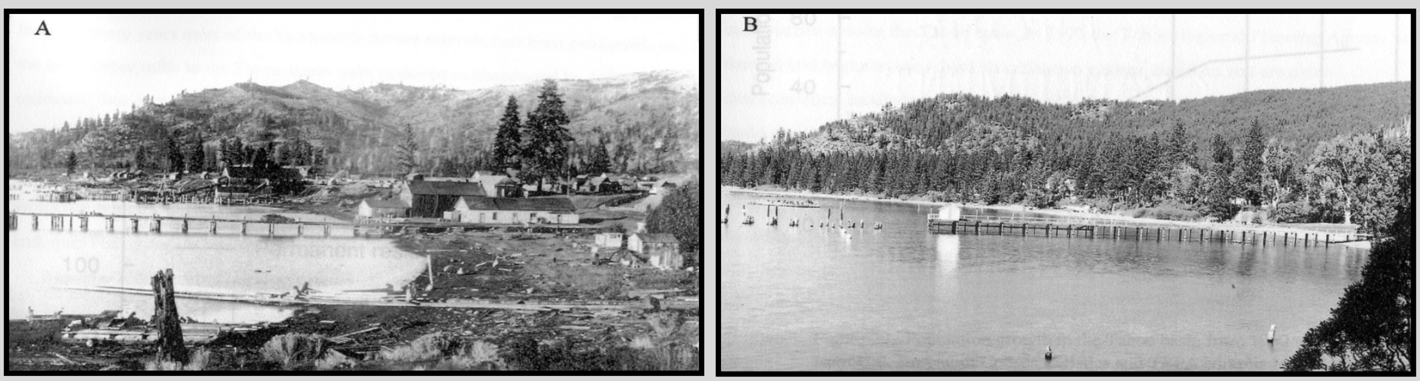


Figure 35. Glenbrook in 1900 with deforested hillside from logging (left); Glenbrook in 1990 with secondary tree growth (right) (Goin 1992)

Soil Moisture & Infiltration

Historical and Current Conditions

Limited data exists on current or historic soil moisture conditions for the 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. Moister drainages and higher organic content are found on north-facing slopes that have denser forests and have burned less frequently. Soil moisture naturally varies with elevation and slope exposure (aspect), as well as with the time of year. From March through August evapotranspiration is supported by soil moisture derived primarily from winter precipitation and snowmelt infiltration. 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 8,500 feet, largely reflecting changes in snowpack (Dettinger et al. 2018). This will affect forest structure and health.

Resource Sensitivity and Exposure

Warming temperatures will raise snowline altitudes significantly, with much more precipitation falling as rain at elevations from lake level (near 6,200 feet) upward to about 9,500 feet, and reduce the depth and duration of snowpacks, This will lengthen and deepen the summer dry period and exacerbate soil water deficits during droughts, likely increasing moisture stress for many forests and yielding changes in vegetation type, density and distribution (Safford, North et al. 2012, McDowell and Allen 2015). Higher snowlines could also reduce the insulating benefits of a snowpack and make forests more vulnerable to damage from increased soil frost. Further, with more intense rainfalls events occurring over shorter periods during the year, there will be less total infiltration to groundwater compared with the historical pattern of a larger number of less intense rainfall events through the year.

CWD will increase for most of the Basin and will be particularly severe in the northern and eastern sections. Dramatic changes in forest health and structure are expected by the end of the century. The drying of soil and air will lead to more insect infestations, tree mortality, and potential wildfires in these areas.

Implications

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 decreases but rates of evaporation from soil and plant transpiration (ET) remain the same or increase (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 critically low. The north and east sections of the Basin will become particularly vulnerable.

In some cases, however, short-term ecosystem accommodation to drought has been observed in the Sierra Nevada. This includes the dieback of trees and the thinning of forested areas by wildfire. These events reduce evapotranspiration demand and leave more water available for soil moisture, stream runoff, recharge and baseflows through the year (Bales et al., 2018). Consequences of tree dieback, however, include increased fire and erosion hazard.

Riparian and Aspen Ecosystems

Historical and Current Resource Conditions

Riparian ecosystems occur at the interface between uplands and streams or lakes, and consist of predominantly hydrophilic vegetation such as willows, alders, and aspen. Riparian habitats are limited in geographic extent but have significant ecological importance because they provide vital connections between the surrounding watershed and the Lake. Sixty-three streams flow into Lake Tahoe and support diverse and large numbers of animal and plant species, including species that almost always occur in these areas (obligates), such as the rare mountain beaver.

Many riparian areas were severely degraded by mining during late 1800s, and by extensive sheep and cattle grazing from the late 1800s to early 1900s. They have recovered to various degrees since that time. Roads in the Basin continue to impact floodplains, and reductions in beaver populations may have limited the extent of riparian habitat. Current threats to riparian areas include the lack of periodic renewing disturbances (e.g., fire, flooding), channel alterations, and drought stress. The encroachment of conifers into riparian areas due to lack of fire, prolonged droughts, and reduced snowpack threatens the long-term vigor and persistence of many aspen stands.

Resource Sensitivity and Exposure

Riparian areas depend directly on the runoff from snowpack in the upper watershed that supplies late season moisture. Riparian habitat is significantly threatened by increases in temperature and subsequent drought stress; changes in timing, volume, and variability of runoff; and increases in fire occurrence and severity. Conifer encroachment 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 competes poorly with conifers. Aspen are found within riparian areas, along meadows, and in stand-alone groves. Aspen stands are relatively uncommon in the Basin, totaling about 2,500 acres, but are an important habitat for many species, and contribute to the overall diversity of the Basin. Decline in the availability of soil moisture threatens aspen groves. The exposure of individual stands will depend on site-specific conditions.

Implications

Riparian systems are currently at risk of wildfire due to high densities of encroaching conifers. Climate change may exacerbate this risk due to projected increased temperatures and drought stress. However, increased high severity fire in forested areas, if not too frequent, may provide an opportunity for aspen to regenerate in riparian areas, as well as to migrate and establish themselves in new areas (Krasnow and Stephens 2015). Riparian areas may also experience warm, low volume streamflows, as well as flashier floods, which could change aquatic communities and increase the degradation of stream channels.

Meadow Ecosystems

Historical and Current Conditions

In the 19th century, intensive grazing and manipulation of drainage patterns degraded most of the Basin's large, iconic meadows by reducing vegetation and concentrating streamflows. Although land managers have curtailed grazing since the 1950s, deepened stream channels (channel incision) remain common. This disconnects streamflows from surrounding meadow floodplains and lowers waters tables. Fire suppression has simultaneously increased densities of lodgepole pine surrounding meadows. This further reduces runoff, dries meadows, and hastens the expansion of conifers into the meadows (Boisrame et al. 2017).

Land managers have prioritized meadow restoration for several decades. They have restored Big Meadow, Cookhouse Meadow, High Meadow, and many others to raise water tables and reconnect floodplains. These meadows have regained capacity to disperse floodflows, retain sediment, accumulate organic carbon in their soils, and support diverse animal communities.

Resource Sensitivity and Exposure

Properly functioning meadows filter water and sediment and create habitat patches that break up forests. Their consistently high water tables maintain wet and productive conditions, even during periodic drought conditions. They are expected to serve as climate refugia for a wide range of bird, fish, and amphibian species. However, recent predictions of meadow resilience to climate change suggest that most Sierra Nevada meadows are not naturally sustainable (Lubetkin et al. 2017). Projected changes in temperatures and snowpack are likely to reduce water tables and dry out many meadows for prolonged periods. This will likely convert meadows to forest or shrubs. Meadows that have consistent groundwater may be good candidates for restoration and conservation.

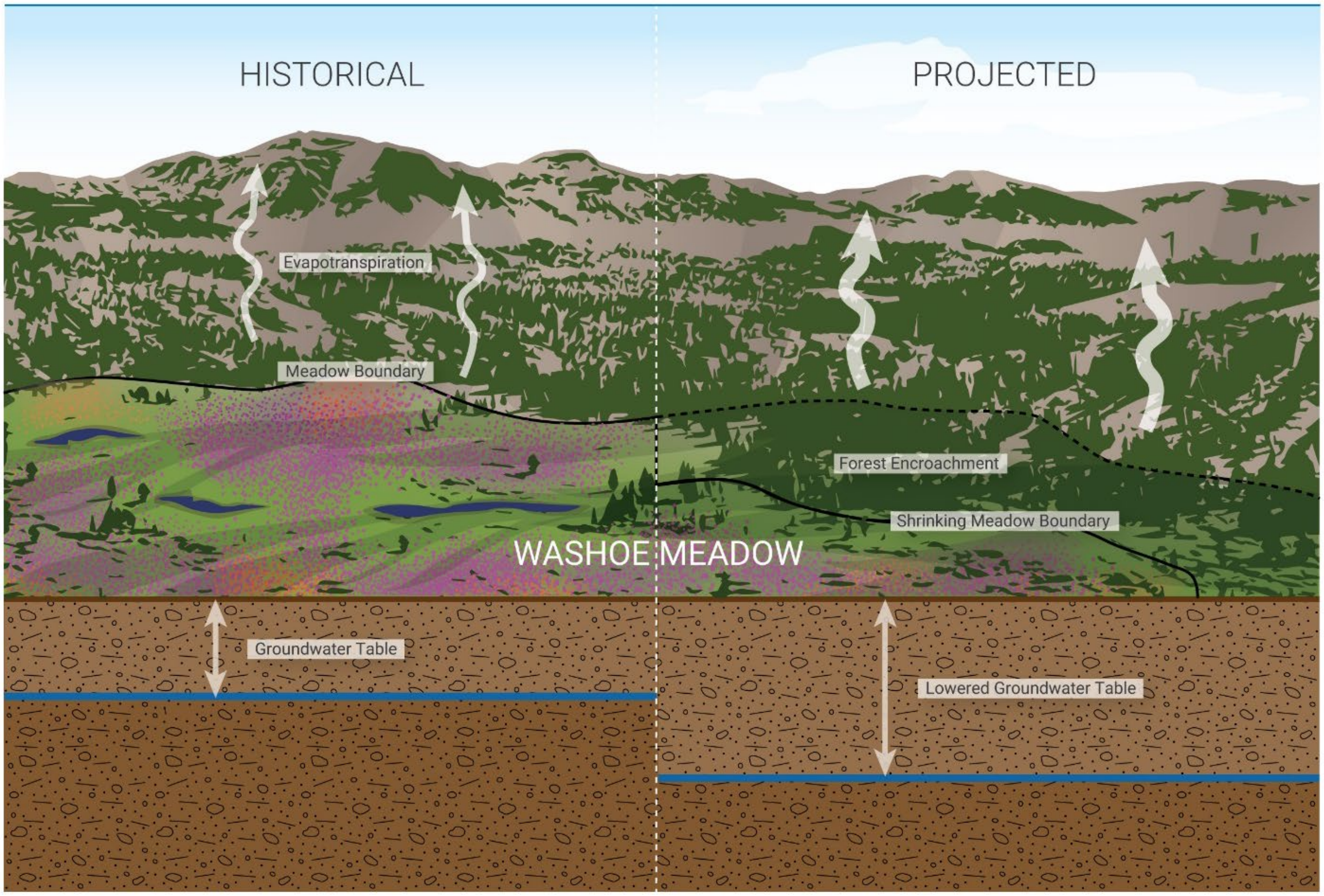


Figure 36. Forest encroachment leads to loss of wetland, meadow, and riparian habitat.

Implications

Reduced snowpack, changing runoff, and increased CWD heighten the need to sustain functioning meadows. The continued reduction in snowpack, and changes in runoff patterns and resulting CWD, escalates the importance of sustaining functioning meadows in the Basin. Restoration needs to better integrate river (fluvial) processes, resolve root causes of degradation, and minimize detrimental disturbances. Otherwise meadows will continue to convert to forests and shrubs (Lubetkin et al. 2017).

Wildlife Connectivity

Historical and Current Conditions

Connectivity is a vital element of conservation. It is generally defined as the degree to which the landscape facilitates or impedes the movement of plants and animals. The Basin contains a patchwork of ecological features and several elevational zones that affect connectivity. The crests of the Sierra Nevada and Carson Ranges that surround the Basin serve as natural barriers to wildlife immigration.

Tree removal, regrowth, and fire suppression dramatically changed the Basin's vegetation in the late 1800s and early 1900s. Today's landscape is relatively homogeneous—long, unbroken stretches of mid-seral stage forests, with few trees older than 100 years. This pattern allows most forest-associated species to readily move from place to place (i.e., creates high connectivity). Wide-ranging, old forest-associated species such as American marten, however, require resting, denning, and roosting structures to move across the landscape. The deficit in old, large trees, particularly in lower elevation zones, is likely to limit such movement.

Roads and other infrastructure have also disconnected various parts of the Basin. They significantly inhibit the movement of certain species, particularly those that roam over large areas such as black bears, mountain lions, marten, bobcats and deer. Towns and communities also obstruct wildlife movement. While current policies limit additional building in the Basin, public agencies may still create additional transportation infrastructure to accommodate growing visitation and car traffic.

Resource Sensitivity and Exposure

Climate change is expected to decrease and fragment habitat (i.e., reduce connectivity). However, it is difficult to predict what changes will have the greatest impact. Prolonged warmer temperatures and spikes in temperature may initially push species to higher elevations. In this case, habitat connectivity will be critical to enable species to adjust. Species on the edge of their temperature ranges are likely to be the most sensitive, particularly cold-adapted species at the warmer edges of their ranges.

Implications

Species associated with limited alpine environments may experience significant habitat loss and fragmentation. Some may modify their behavior accordingly. For example, the black bear may rely more on human food sources, and seek human structures for resting and denning, if access to upslope food and habitat becomes scarcer.

Higher temperatures may also facilitate the immigration of species that otherwise do not tolerate cold climates. These may include non-native species as well as highly adaptable and competitive generalist species. Reduced precipitation and greater variability in precipitation could offset such immigration but is not likely to entirely counter increasing temperatures.

Reduced streamflows and shorter periods of ponding and soil saturation are likely to reduce the connectivity of streams, lakes, ponds, aspen stands, and meadows, and the associated aquatic organisms. Meadows are expected to be highly vulnerable. Two thirds of the meadows along the west shore may not be able to provide adequate refugia for meadow species under future climate scenarios because of reduced connectivity and wetness (Morelli et al. (2016) and Moher et al. (2017). Species that are less tolerant of warmer water will also be among the most vulnerable.

Future warming and drying also are likely to exacerbate vulnerabilities. For example, many non-native species are generalists and adapt well to altered environments. On the west shore, approximately 80 percent of streams have dams or other structures that prevent the movement of fish and other aquatic organisms, and nearly half (47 percent) of these contain more non-native than native aquatic species. As streamflows decline, native species will be even more vulnerable to competition from non-native generalists. Generally, such species reduce genetic, biological, and functional diversity. Similarly, 75 percent of the west shore is within a quarter mile of a road or trail. Anticipated increases in visitors, with more people seeking refuge in Tahoe's relatively cooler climate, will create additional disturbance near roads and trails that disrupt otherwise connected vegetation conditions.

Economic Implications for Natural Resources

The Basin's unique character derives from its natural resources, which make it a desirable place to live and visit. Climate change is projected to impact the resilience and functioning of many of Tahoe's ecosystems. This section translates the implications of climate change for natural resources into economic impacts. Because not all aspects of ecosystems are bought and sold in a traditional market, economists often use an ecosystem service framework to estimate the non-market value of the implications. Such a framework identifies relevant ecosystems in the area, characterizes how climate change will alter the ability of each ecosystem to provide services, and values the change in the quality or quantity of each service provided.

The implications detailed earlier focus on two sub-systems, Lake Tahoe and the Uplands, and cover eleven resources. Figure 37 shows the vulnerability of each resource combined with its relative economic value. The size of the bubble represents the economic value at risk; resources with larger bubbles have more economic value based on the considered ecosystem services, and smaller bubbles have less value. Resource managers may want to consider both the most vulnerable resources, in the top right of the graph, and the resources of high value indicated by the larger bubbles.

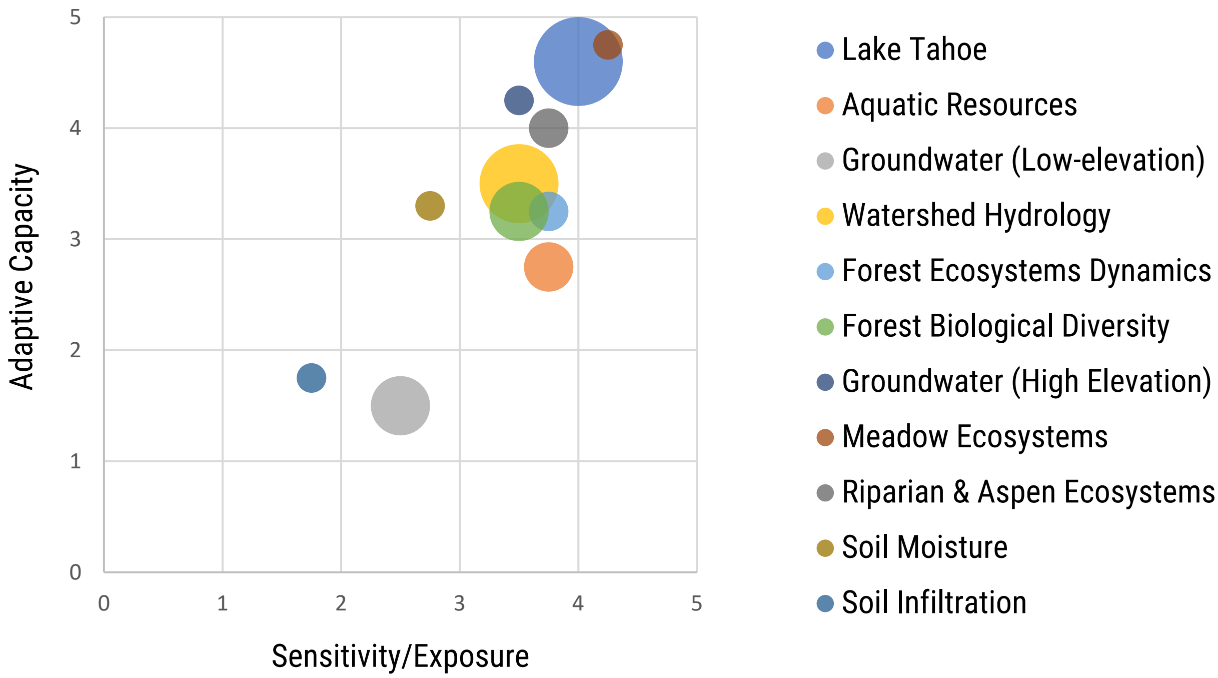


Figure 37. Basin natural environment economic value and vulnerability

Figure 37 shows that Lake Tahoe is both a valuable and vulnerable resource. Other vulnerable resources, such as aquatic resources (lakes and streams), riparian and aspen ecosystems, and high-elevation groundwater, have less direct economic value. Watershed hydrology and forest ecosystem dynamics and biological diversity, although slightly less vulnerable, have higher values.

Table 1 lists the economic impacts associated with aforementioned climate change implications. In addition to the two sub-systems, the table also includes the impacts of general changing climate conditions (e.g. health impacts and other ecosystem service losses). **Bolded** values in the economic impact column focus on high-value ecosystem services and cross-cutting climate hazards and are discussed in more detail. The remaining impacts are not discussed due to either lack of data on physical impacts and/or valuation inputs, or due to low anticipated magnitude of impacts.

Table 1. Physical and economic impacts of climate change on Basin environments

RESOURCES	IMPLICATIONS	ECONOMIC IMPACTS
Lake Tahoe Sub-system	Decrease in Lake Tahoe clarity Lower Lake Tahoe levels More competition for aquatic species Less native vegetation	**Decreased property values (aesthetics)** Lost recreation value (aesthetics, wildlife viewing, fishing) **Lost recreation opportunities (access)** Increased water supply costs (water availability) Lost biodiversity
Upland Sub-system	Diminishing meadows ecosystems Riparian and aspen ecosystems encroached by conifers Altered distribution and interaction of species Compromised forest ecosystem dynamics and function Riparian and Aspen Ecosystems Encroached by Conifers	Increased flood damages (flood attenuation capacity) Lost biodiversity value Increased water supply costs (water filtration) Lost recreation value (aesthetics, wildlife viewing, fishing, hunting) **Increased wildfire damages (fuel increase)** Decreased timber revenues
Cross-cutting Climate Conditions	Temperature and snowpack	**Lost recreation value (winter recreation access)** Increased damages associated with premature death (extreme heat mortality) Decreased wages (lost labor hours due to extreme temperatures)
Cross-cutting Climate Conditions	Climatic Water Deficit, Wind Speed and Wildfire	**Increased wildfire treatment and suppression costs (wildfires)** **Increased health costs (wildfire smoke impacts)** **Lost ecosystem services** Increased wildfire property damages

Lake Tahoe

The Lake provides economically valuable services, including recreational opportunities, aesthetic benefits, habitat for a range of species, and clean water. As a nationally important site, the Lake provides value to residents and visitors, as well as to individuals who may never visit yet value knowing the Lake exists in a high-quality state (this is called a “non-use value”).

Lake Tahoe’s exceptional clarity has been declining from more than 50 years. Changing temperatures, precipitation patterns, and wildfire events will further threaten lake clarity in the future. Prior studies estimating the value of lake clarity typically use revealed preference methods (also called hedonic studies). These relate a person’s willingness to pay for properties and recreational opportunities to water clarity measures. Tahoe’s extraordinary baseline clarity makes it difficult to transfer results from other locations. However, a hedonic study in New Hampshire found that housing prices increased by 0.9 to 6.6 percent per one-meter increase in Secchi water clarity measurement in nearby lakes (Gibbs et al. 2003).

Declining water quality from increased thermal stratification also has economic consequences. These include increasing the cost of water supply treatment, reducing welfare benefits (i.e., health, happiness) associated with recreational trips, and increasing the risk of waterborne illness.

Lake level fluctuations also have economic impacts. A 2003 study at Lake Almanor, about 130 miles northwest of Lake Tahoe, found that for each additional foot of exposed shoreline, property prices dropped by about $150 dollars ($2018) (Loomis and Feldman 2003).

Wildfire

Wildfires are predicted to grow in both frequency and intensity in the future. In the Basin, the total area burned by wildfires in the end of the century (2090-2100) is predicted to be 61 percent higher than that at the beginning of the century (2010-2020). Moderate and high burn severity areas are projected to increase the most, at 89 and 80 percent, respectively (LTW 2019).

Wildfire smoke plumes can affect air quality miles away from the burn location. The fine particles in smoke infiltrate lungs, eyes, and noses, and can lead to medical conditions ranging from minor irritation to chronic respiratory illness and even premature death. Total annual health-related damages from the largest projected event by mid-century (2039) will cost $19.5 million (estimates range from $7.4 million to $40.8 million, depending on the model and weather scenarios) (LTW 2019).

From 2020 to 2100, average annual wildfire treatment costs are expected to be about 30 percent higher than 2010 costs, and suppression costs are 55 percent higher than 2010 costs (LTW 2019).

Lost ecosystem services from vegetation impacted by increased wildfire activity, particularly mature vegetation, can be a large category of damage. A habitat equivalency analysis (HEA) can be performed to estimate this loss.

Winter Recreation

Alpine skiing, a high value activity, is vulnerable to shortening seasons. There is strong evidence suggesting that snowpack will decline across the Basin in the next century (see Figure 7). A 2017 study by Wobus et al. uses information on expected snowpack and snowmaking conditions to estimate changes in expected season lengths at winter recreation sites across the country. The Basin's ski season is expected to decrease by 19 and 52 percent by 2099 under RCP 4.5 and RCP 8.5, respectively, across all sites.

Ski area visitation is highly correlated with ski season length (Wobus et al. 2017). Assuming a linear relationship between season length and visitation, and therefore revenues, Basin ski areas are projected to lose $270 million in revenues annually under RCP 8.5 by 2090, or about 52 percent of baseline annual revenue for Basin ski areas based on visitation data (Stewart 2019). Even under the more modest RCP 4.5 scenario annual losses are projected at $100 million per year by 2090.

These estimates do not account for any projected growth in visitation independent of season length (e.g. growth related to population increases). They also do not include additional lost revenues for ski areas that may become unprofitable and close operations. It is likely that certain ski areas would completely close instead of operating under a shortened season year after year. Visitors not able to ski may still choose to visit for non-ski activities. However, these tend to be lower revenue drivers and would require investment in management and facilities to ensure access.

Overview of the Communities Sub-System's Vulnerability

People also make the Basin a special place. The Basin hosts a wide range of visitors, tourists, and residents that require essential services and are subject to the implications of climate change. For example, a shortening and wetter winter season could significantly impact the winter tourism economy; or a landslide that shuts down one of the highways could affect commute time.

The IVA focuses on resources and assets that provide critical services and correlate directly with public wellbeing and economic health. The IVA analyses the following communities sub-system resources and assets:

- Transportation, Communications, Water, and Energy Infrastructure
- Cultural Resources
- Recreation
- Public Health and Safety

The sub-system has the following key vulnerabilities.

- Roads, bike paths, and key infrastructure are threatened by increased risk of wildfire, flooding, erosion, and landslides.
- Recreation use is impacted by low snowpack and extreme weather events.
- Public health is threatened by smoke from wildfires and extreme heat events.
- Cultural heritage is threatened by increased risk of wildfire.
- Traffic in the Basin is likely to increase as visitors seek cooler temperatures.

Transportation, Water, Energy, and Communications Infrastructure

Connections to the outside world provide the Basin with tourism, freight and goods, electrical power, wastewater treatment and disposal services, and communications. The Basin's geography significantly influences the vulnerability of its infrastructure. The mountains restrict linkages to surrounding networks and communities, forcing critical connections to span long distances through potentially vulnerable terrain. These constraints reduce the number of deliberately redundant infrastructure connections and introduce potential chokepoints. Additionally, vulnerabilities which may degrade or disrupt one service (such as electricity) can have cascading impacts which disrupt others (such as water delivery, communications, and transportation systems). These infrastructure networks are vulnerable to climate change.

Historical and Current Conditions

Transportation

Vehicle traffic on paved roadways dominates transportation in the Basin. Six highways provide the only external access to the Basin (other than the Lake Tahoe Airport, which is not used for major commercial service). Basin communities lie mostly around the shores of Lake Tahoe, so many only have an external access route to the north or south of their community. The highways serve as community main streets and support the majority of traffic, including transit system buses, freight trucks, passenger vehicles, and emergency service vehicles. Several bus systems serve the Basin, although most visitors enter the Basin by private vehicle. The Basin's transportation infrastructure also includes non-arterial streets, rural roads, unpaved roads, and recreational trails.

Energy Infrastructure

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 Infrastructure

The Basin faces a unique water challenge: laws to protect Lake Tahoe mandate that communities export all wastewater, both treated and untreated. Placer County communities pump their untreated wastewater via the Truckee River Interceptor pipeline to a wastewater treatment plant near Truckee. Other communities treat their wastewater at one of three treatment plants located in the Basin, and then export it. Local utilities own and operate the Basin's water infrastructure, including the South Tahoe Public Utilities District (STPUD) in El Dorado County, Tahoe City Public Utility District and North Tahoe Public Utility District in Placer County, Incline Village General Improvement District in Washoe County, and Douglas County Sewer Improvement District No. 1, as well as some additional smaller utilities.

Communications Infrastructure

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. Cal.net also provides wireless internet service in parts of the Basin. The Basin's data networks connect to fiber-optic trunk lines outside the Basin, including Windstream lines in Carson Valley and Truckee. Verizon, AT&T, T-Mobile, and MetroPCS provide wireless data in the Basin. Twenty major cellular and AM/FM radio towers are located in the Basin.

Climate Change Hazards Impacting Transportation and Infrastructure

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

Hazard 1: 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 may disrupt critical roadways—many of which have few alternative routes—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. Wastewater removal and treatment infrastructure in the Basin is particularly vulnerable to flooding. The STPUD wastewater treatment plant is partially located in a 100-year flood zone, although land survey data shows that 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.

Hazard 2: 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, are important risk factors for landslide and debris flow. Landslides can severely damage infrastructure located on or below a sliding slope, such as roads, pathways, power and communications lines, water storage tanks, and pipelines. Landslides also cause lengthy disruptions as tons of rock, soil, and debris must be removed to restore service. The highways connecting Basin communities traverse high mountain passes, canyons, and cuttings alongside potentially hazardous slope zones. In areas already prone to landslide hazards (e.g., State Route 89 around Emerald Bay), projected increases in the frequency and intensity of extreme precipitation events may increase the frequency of landslides.

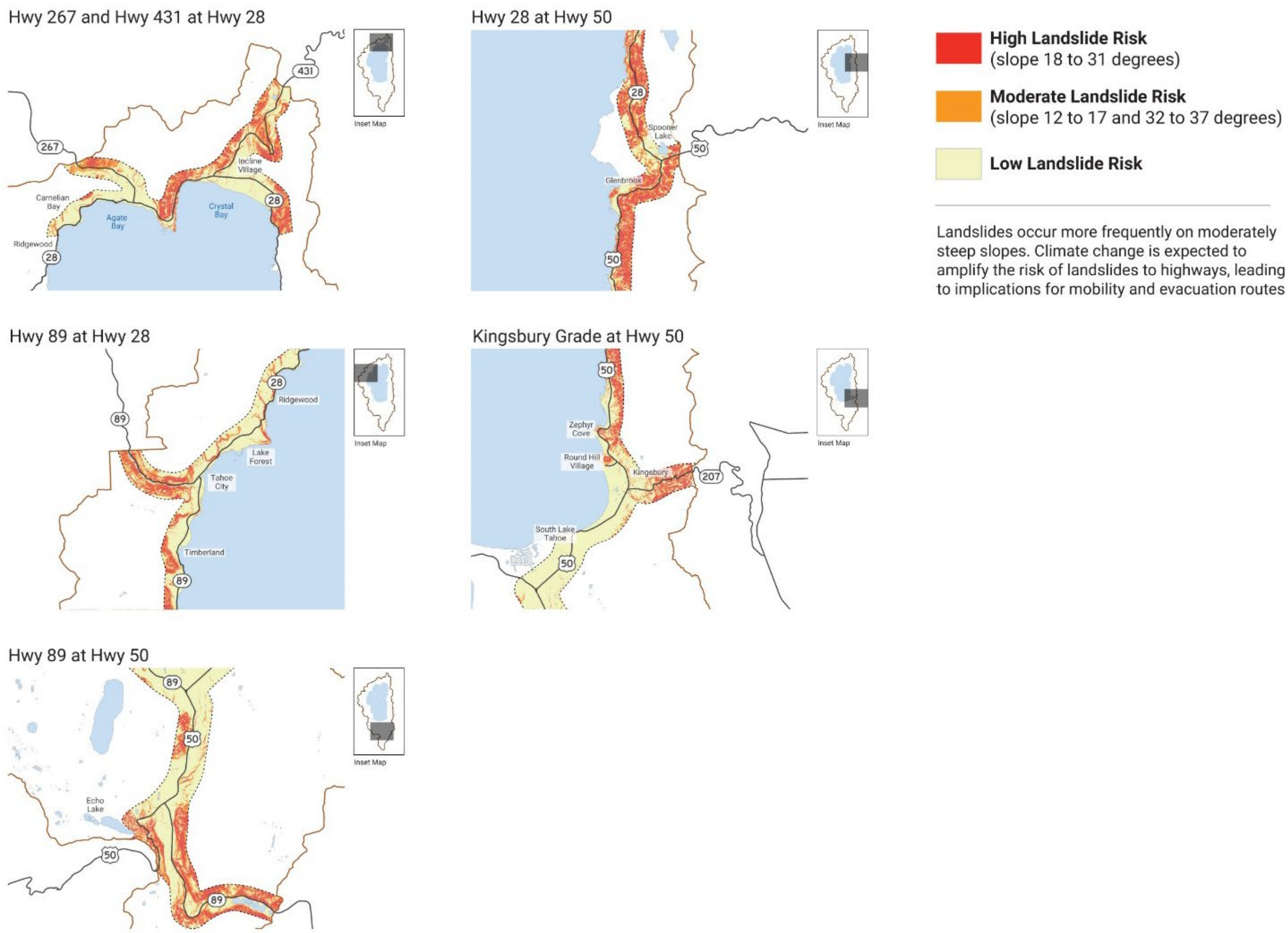


Figure 38. Landslide risks surrounding Basin highways (current conditions). Climate change is expected to amplify the risk of landslides to highways, leading to implications for mobility and evacuation routes.

Hazard 3: 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.

Hazard 4: Wildfire

The current wildfire threat to infrastructure varies significantly across the Basin, depending mainly on the proximity of infrastructure 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 (Figure 39). Throughout the rest of the Basin, the direction and degree of change vary across emissions scenarios and timeframes.

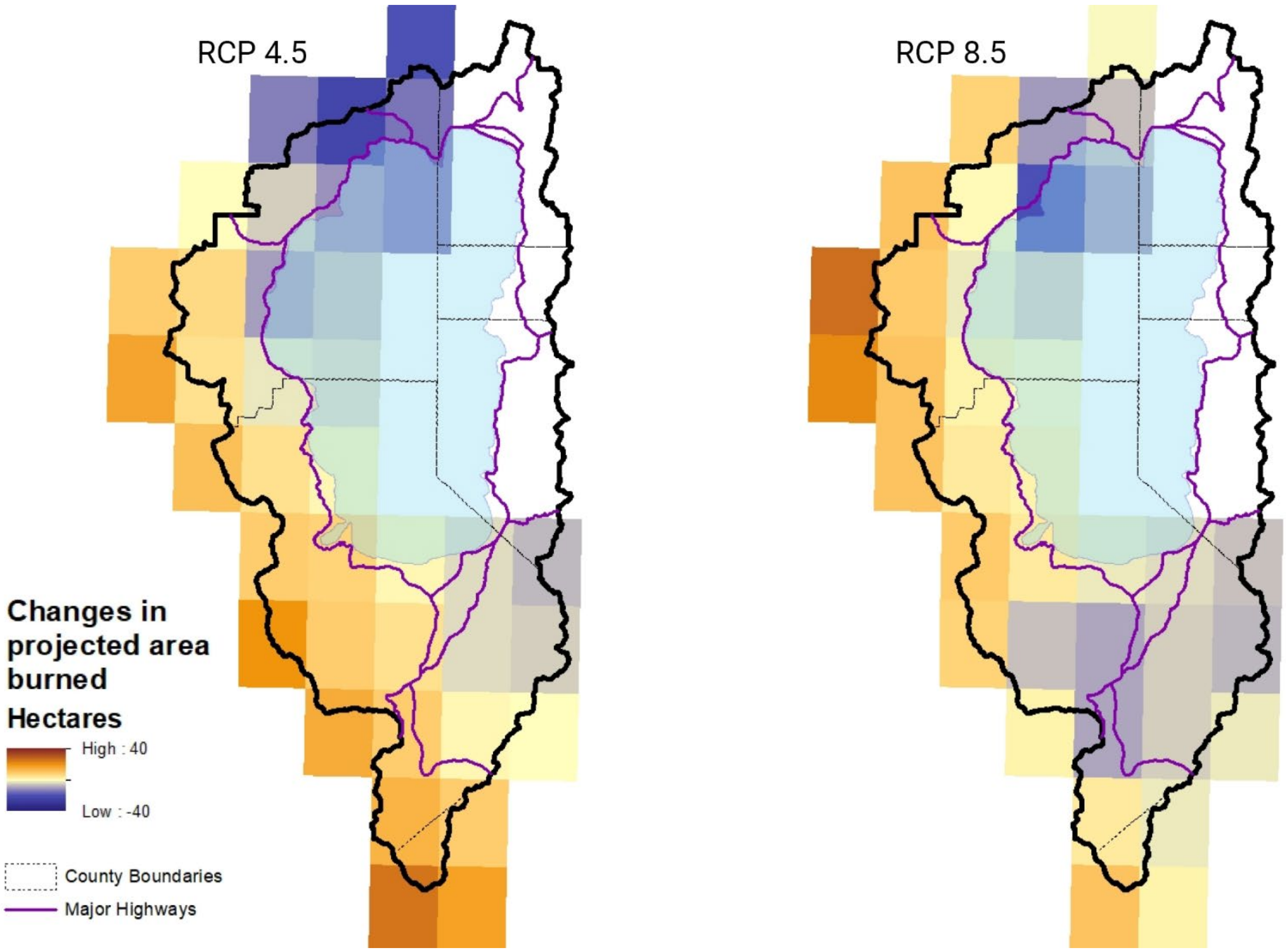


Figure 39. Projected change in wildfire area burned by the end of the century for RCP 4.5 and RCP 8.5

Due to the large-scale nature of wildfire, fires threaten broad disruption of the Basin's infrastructure. 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.

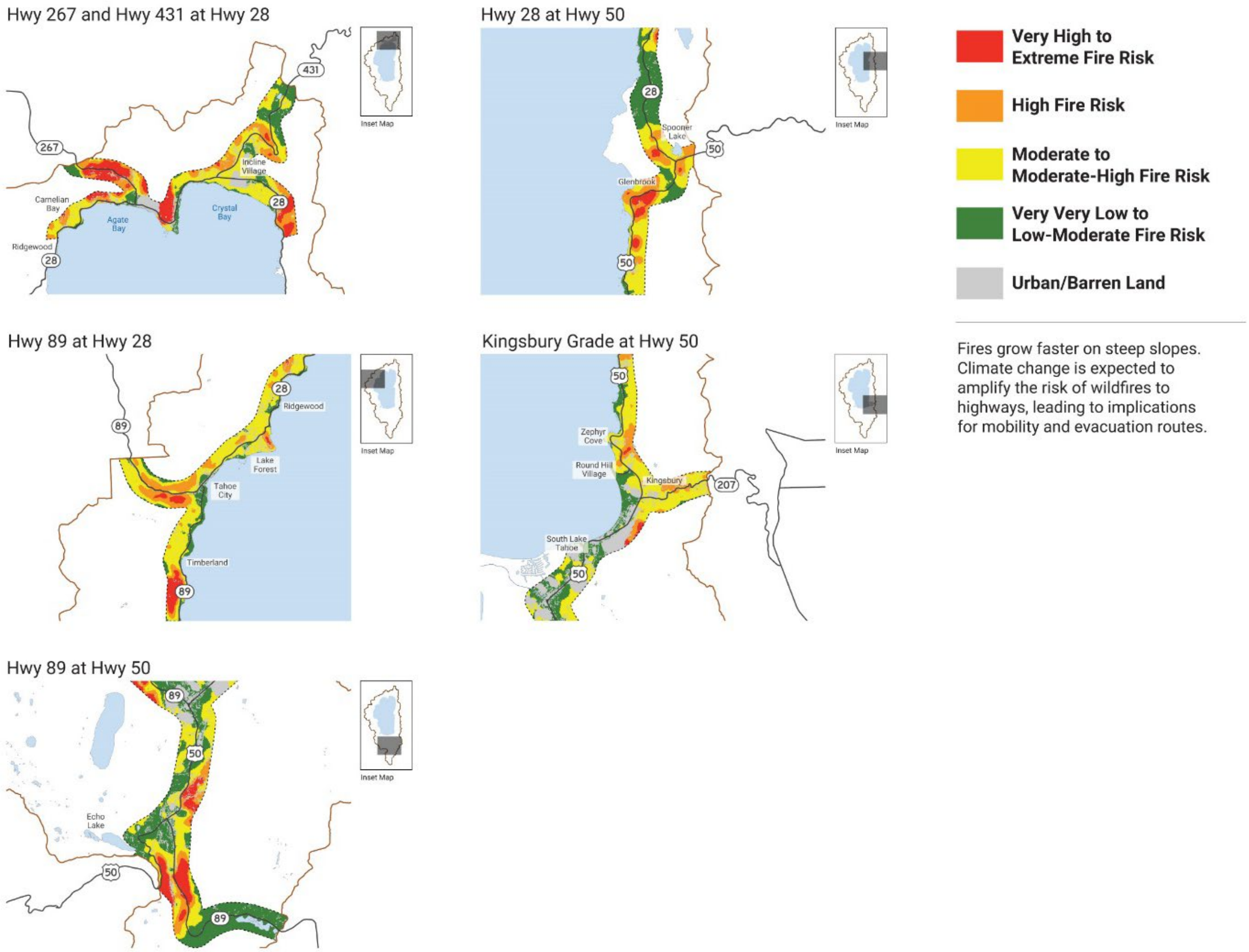


Figure 40. Wildfire risks surrounding Basin highways (current conditions). Climate change is expected to amplify the risk of wildfires to highways, leading to implications for mobility and evacuation routes.

Hazard 5: Temperatures

Although the primary hazardous effect of higher global temperatures in the 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, thus 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

Older infrastructure systems, mostly constructed in the 1950s and 1960s, undergo constant change through maintenance, improvement, and further construction. Long-term infrastructure changes are driven primarily by the aforementioned natural hazards, as well as growth in population and tourism, and changes in technology.

- Population growth in the megaregion (including the Tahoe-Reno Area, San Francisco Bay Area, Central Valley, Northern Sierra Nevada Foothills and Carson Valley) challenge the existing capacity and increase the significance of vulnerabilities to climate hazards. As more users rely on the systems, any disruption affects more people. Climate change is also likely to increase traffic in the Basin as tourists visit the region to find cooler temperatures.
- Technologies can increase vulnerability by increasing the interdependence of infrastructure systems. The growth of digital communications has made data connectivity more important for transportation (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) increases reliance on existing systems. Finally, infrastructure improvements in general increase the interconnectedness of infrastructure systems.
- An elevated number of extreme heat events is expected to occur in parts of El Dorado County outside of the Basin, including locations as close as ten miles from the Basin, especially in the latter half of this century. This is likely to increase visitation to the Basin as people avoid extreme heat.

Asset Sensitivity and Exposure

Potential impacts to the Basin's infrastructure systems and assets were modeled to assess their relative vulnerability to climate-related hazards, and to identify the drivers of those 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. By assessing the exposure and potential impacts of infrastructure systems, it is possible to prioritize vulnerabilities for resilience-building and adaptation actions. Table 2 describes key impacts. Figure 41 graphically summarizes the exposure of key infrastructure to each hazard, and the impact were the hazard to occur.

Table 2. Key infrastructure vulnerabilities by system and asset, and by 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 percent Basinwide by mid-century.
Main Roads and Landslide	About three-fourths 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 about 35 percent Basinwide by mid-century.
Main Roads and Wildfire	Nearly every highway segment in the Basin (except U.S. Highway 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 percent Basinwide by mid-century.

Infrastructure and Climate Hazard	Reasons for Higher Vulnerability
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 percent 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 Basinwide is projected to increase by about 21 percent.
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 percent for six modeled catchments in the Basin by mid-century.
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 percent 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 contact with vegetation, which could spark fire events. Heat waves in the greater region are projected to increase in frequency and intensity by mid-century.

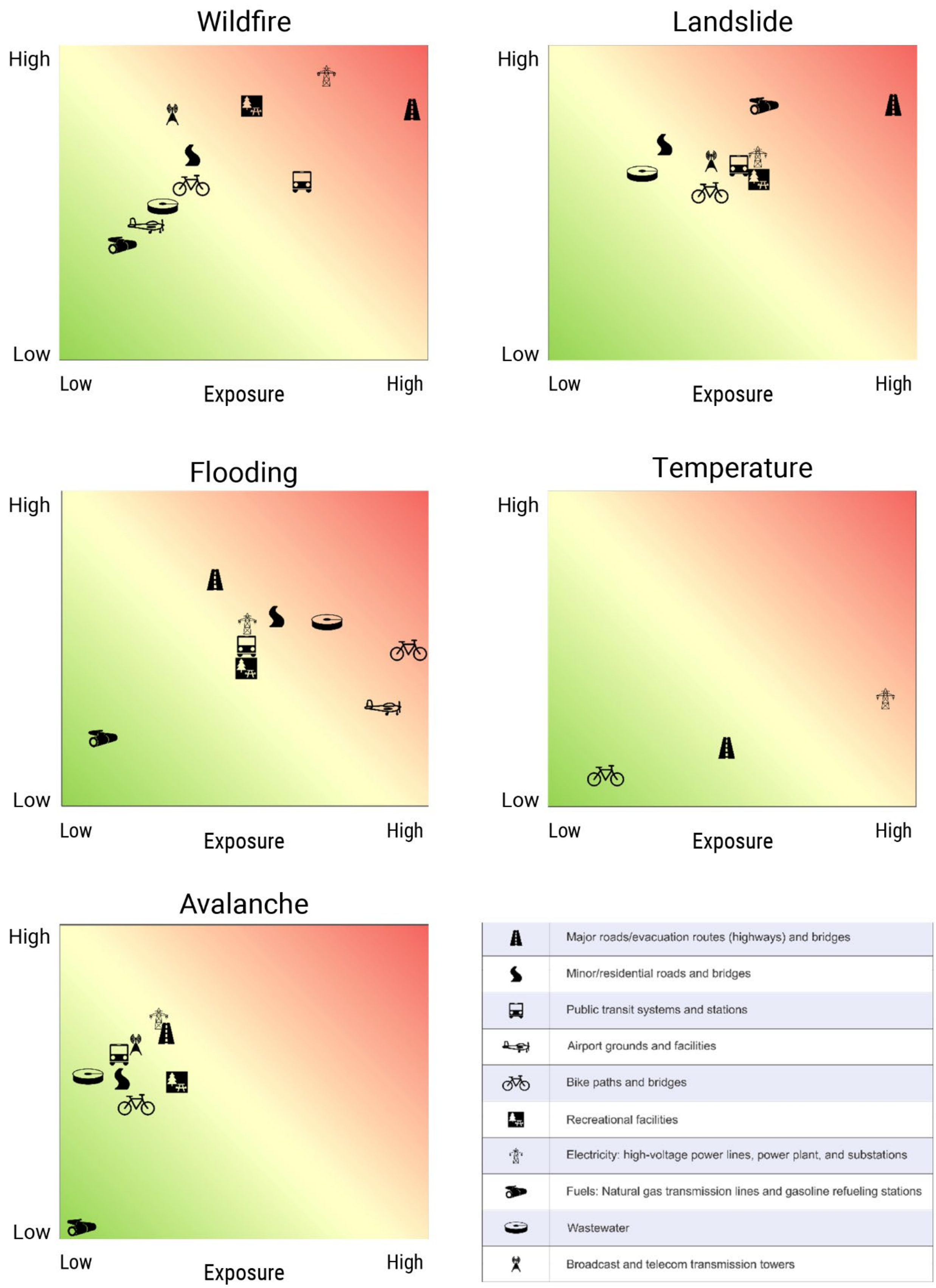

Wildfire
High
Low
Low
Exposure
High
Landslide
High
Low
Low
Exposure
High
Flooding
High
Low
Low
Exposure
High
Temperature
High
Low
Low
Exposure
High
Avalanche
High
Low
Low
Exposure
High
Major roads/evacuation routes (highways) and bridges
Minor/residential roads and bridges
Public transit systems and stations
Airport grounds and facilities
Bike paths and bridges
Recreational facilities
Electricity: high-voltage power lines, power plant, and substations
Fuels: Natural gas transmission lines and gasoline refueling stations
Wastewater
Broadcast and telecom transmission towers

Figure 41 (preceding page). Exposure and potential impact from climate change hazards for infrastructure systems, for 2050 for RCP 8.5. Assets with lower vulnerability are shown toward the bottom-left and those with higher vulnerability are located in the upper-right.

Cultural Resources

Historical and Current Conditions

Lake Tahoe is the center of the aboriginal territory of the Washoe Tribe (Tribe). The forced removal and relocation of the Tribe to reservation lands have impacted the Tribe's traditional practices, economy, and social systems. These events have also affected the Basin's ecosystems, including the eradication of the grizzly bear, wolf, and naturally reproducing Lahontan cutthroat trout, and the decline of other wildlife populations. Seasonal movements of Washoe people, including moving to and from summer camps around Lake Tahoe, provided an important means of responding to changes in climate. Removal and relocation greatly reduced this adaptive capacity. Indigenous burning was an important part of the Basin's frequent fire regime. It was common in the fall as Washoe moved to lower elevations for the winter. Many traditional foods and other resources important to the Washoe are no longer harvested, due to reduced availability, reduced access, and disruption of traditional activities and knowledge. The Washoe Tribe is restoring and maintaining cultural heritage practices in the Basin through partnerships with federal and state agencies. These efforts increase adaptive capacity. However, the diminished presence of the Tribe constrains such opportunities.

Climate change may affect the Tribe's cultural heritage in the Basin. This includes plants, wildlife, artifacts, places, sense of well-being, and other less tangible values. The Washoe, like many indigenous groups, are particularly concerned with the potential for climate change to impact water, food, medicines, and traditional knowledge. Specific elements that have been especially important to the Tribe include the following:

- High quality water, which the Washoe consider to be the most sacred resource;
- High quality air;
- Native fishes, especially Lahontan cutthroat trout and whitefish, shellfish, and terrestrial wildlife;
- Plants of high cultural importance, many of which were foods, basketry material, and medicines;
- 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; and
- Traditional knowledge and cultural practices that need to be actively applied to sustain or build community capacity to thrive.

Implications

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.

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. However, those tree species require many decades to establish, mature, and produce nuts, so such potential shifts are unlikely to offset near-term losses in forest food productivity.

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 negatively affect 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 re-sprout (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., a mosaic of small patches of burns of varying severity), 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 for vigorous growth and productivity.

Severe wildfires can also 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 non-native fishes, so such events could also present opportunities to actively promote cultural heritage through ecological restoration.

More intense fires could also damage archaeological artifacts and cultural sites. Such fires can cause large trees to fall and burn, contribute to extreme soil heating, and increase soil erosion. High-severity fires may also deter Washoe people from visiting areas due to safety concerns and impacts to sense of place, especially when areas become less recognizable or cultural sites are damaged.

Climate change may reduce access to desired resources and increase barriers to traditional activities such as burning. In particular, shifting fire regimes may increase the risks of intentional burns, shorten the windows for such burns, and erode public tolerance of smoke. As a result, opportunities for using prescribed fire (by public agencies) and cultural fire (by tribal members) may decrease. Furthermore, changes in climate and increased disturbances from wildfires may facilitate spread of invasive plants such as cheatgrass, which could complicate efforts to reinstitute traditional burning practices.

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 (e.g., youth, elderly), and low income (making it more difficult to avoid smoke, for example, by temporarily relocating).

Finally, several implications of climate change may reduce food security and increase associated physical and mental health. These include reduced access to traditional foods, reduced access to culturally important places, and fewer opportunities for cultural practices.

Winter and Summer Recreation

Historical and Current Conditions

The 2015 National Visitor Use Monitoring Program (NVUM) showed an almost equal distribution of recreation visits to the Lake Tahoe Basin Management Unit (LTBMU) for warm-weather (42.3 percent) and winter activities (41.4 percent). Warm-weather main activities were viewing natural features (20.3 percent) and hiking/walking (13.6 percent), and winter main activities were downhill skiing (41.3 percent). Estimated annual expenditures in the local community (i.e., a 50 mile radius) are higher for recreation visits from non-local and infrequent visitors than from local and frequent users.

A variety of stressors impact recreation settings and opportunities in the Basin. These include urbanization, uses of and demands on local areas, fire suppression and resulting ecosystem conditions, and climate change.

Sensitivity and Exposure

The Basin offers diverse outdoor recreation and nature-based tourism opportunities. An increase in recreation is projected regardless climate change effects. Nationally, recreation in the Pacific Coast Region, which includes Lake Tahoe, is viewed as the most resilient to climate change. Nevertheless, some sensitivities to climate change effects are noteworthy.

Climate change projections include overall increasing average temperatures, an extended warm season, and more incidences of high heat days. An extended warm season is likely to increase visitation to and associated recreation in the Basin. Currently many developed recreation settings close during the colder seasons of the year. Demand may increase for extended access to these settings, which may in turn result in extended impacts to natural systems. Temperature increases will also likely shift the types of activities and settings visitors will seek out, moving demand closer to water bodies and well-shaded areas.

While a shift from snowfall to more rain may impact winter demand for downhill skiing, snowmaking technologies will preserve the majority of use, especially at higher elevations, though higher costs may be involved. Cross-landscape uses such as snowmobiling, which covers a lesser portion of the overall use in the Basin, may be negatively impacted as snowpack depths decline. Atmospheric river events 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 surrounding region is projected. More frequent and intense fires have already affected recreation and tourism in the Sierras in a number of ways. Applying these experiences to the Basin, fires in the region may affect access to the Basin. Second, fires may close areas due to safety concerns or needs to recover from fire and post-fire effects. Third, smoke may affect viewsheds and degrade air quality, resulting in warnings to avoid strenuous or even any outdoor activities. Prospective visitors may shift plans accordingly, thus reducing the number of days they visit, changing the locations they visit, or cancelling plans their visit altogether.

Implications

Increases in recreation participation will add additional demand on natural systems and public land managers. A 2015 summary of Basin visitor surveys suggests that while most recreation users are satisfied with the overall experience, including environmental conditions and signage, they are less satisfied with access. Increased demand may decrease overall satisfaction.

Agencies will need to increase staffing, capacity, and corresponding resources to maintain the quality of experiences.

As noted earlier, the need to keep sites and areas open longer instead of closing during cold weather will require shifting staffing and management. Increasing use across seasons may impact natural systems and require more attention to seasonally permitted impacts and types of uses.

Extreme weather events (e.g., high heat days, extreme fire weather, extensive rainfall, heavy snowfall, storms, and floods) can have short-term impacts on access and available activities. Resulting resource damage may leave areas or developed settings closed for extended periods. Wildfires will have similar effects, though smoke may impact recreation visits and quality across a larger area, reducing the overall benefits to the local economy and reducing the public health benefits from outdoor recreation participation.

Climate change will impact recreation infrastructure such as trails, roads, and highways. Increased stream flows from heavy rainfall events and rain-on-snow event flooding, and debris flows induced by storms and intensified by wildfires, will make drainage structures vulnerable to damage. Less snowpack will allow earlier seasonal use of roads and trails and create more damage due to saturated soils. More severe fires may damage trails, bridges, buildings, and other facilities. The ability to recover from these impacts depends on a complex set of influences, and will place greater reliance on partnerships and collaboration.

Public Health and Safety

Historical and Current Conditions

Climate change will create several public health and safety challenges within the Basin. Increasing wildfire and related smoke exposure, and greater heat-related mortality and morbidity, are the greatest concerns. Indirectly, 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 well-being. The frequency and size of wildfires is expected to increase in the Basin, potentially leading to more smoky days and lower air quality.

Sensitivity and Exposure

While all individuals are susceptible to the health risks posed by climate change, certain subpopulations face increased risk. These include the elderly, young children, individuals with pre-existing medical conditions, and individuals with outdoor occupations. Socio-economic factors also affect a population's health risk. For example, individuals who 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 to avoid extreme weather.

Implications

Health Effects of Wildfire Smoke

Smoke exposure directly threatens human health. Threats include adverse respiratory outcomes, such as asthma; an elevated risk of cardiovascular and cerebrovascular conditions; all-cause mortality (i.e., harmful exposure); and evidence of adverse birth outcomes. Future wildfires in the Basin are expected to be more frequent and intense, which could create longer spans of smoke and lower air quality. The duration of smoke exposure to smoke contributes significantly to adverse respiratory outcomes; more frequent wildfires could increase such outcomes. Furthermore, as discussed in the Transportation Infrastructure section above, the risk of a major wildfire in the Basin could create a potentially health threatening situation, especially if the wildfire has shut down one of the primary routes in and out of the Basin.

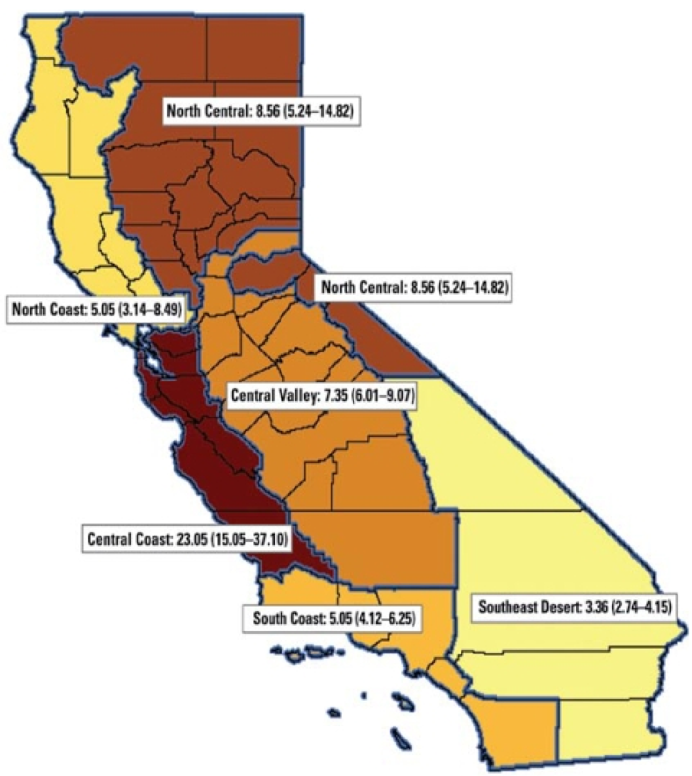
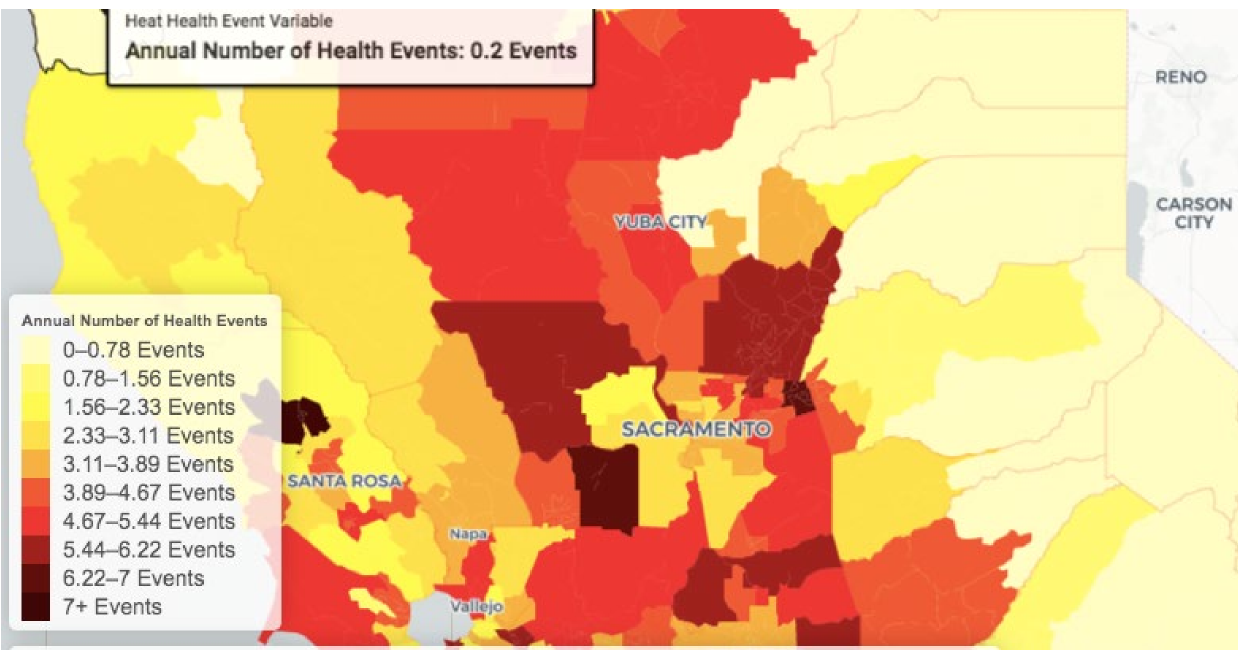


Figure 42. Risk ratios for heat-related emergency department visits during the 2006 California heat wave (Knowlton et al. 2009).

Health Effects of Extreme Heat Events

Increasing frequency, intensity, and duration of extreme heat events pose serious public health risks. These include elevated heat-related morbidity and mortality from heat stroke, exhaustion, and dehydration. As the number of extreme heat events increases, communities in the Basin will likely experience increased risk. For example, a study of the 2006 California heat wave found significantly elevated risk ratios in counties around the Basin for heat-related hospitalizations (Figure 42).

This risk is especially concerning for vulnerable and isolated individuals and communities that are not well adapted to temperature extremes. The California Heat Assessment Tool (CHAT) projects that census tracts in the Basin are relatively less likely to experience extreme heat events than other regions of California (Figure 43). As noted above, extreme heat events will have disproportionately adverse effects on various vulnerable populations. For example, according to the CHAT, ten to 15 percent of the workforce work in outdoor occupations in several census tracts around Lake Tahoe. This percentage is well above the state average and thus indicates an important public health vulnerability.



Source: California Heat Assessment Tool

Figure 43. Projected number of extreme heat health events (2041-2060)

There is also a potentially adverse interaction between extreme heat events and wildfire, as both become more frequent due to climate change. Extreme heat can exacerbate the public health effects of wildfire smoke exposure. 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 increase the demands on emergency response services. If local institutions are not adequately prepared, additional adverse outcomes are possible due to the added strain on the community's public health resources. Additionally, potentially non-functioning communications infrastructure during an emergency evacuation poses a direct threat to public health and safety.

Economic Implications for the Basin's Communities

Historical and Current Conditions

The Basin economy generates over $5 billion in outputs annually. Reliable infrastructure plays a vital role in supporting generation of these outputs. Without adaptation, transportation systems are particularly vulnerable. These face up to $75 million in annual costs of climate hazards by 2090, which is an 11-fold increase relative to current conditions. Disruptions to electricity distribution, water supply and treatment, the communication network, recreational trails, and housing and buildings could also be significant, and are discussed qualitatively below. In terms of wildfire risk, Placer and El Dorado counties have $911 million and $1.2 billion of property in areas with a high to extreme levels of wildfire threat.

Tourism is the largest driver of the Lake Tahoe Basin economy, at 40 percent of the total. This share has been declining as the health care, financial, and technology sectors have grown. However, the remaining high degree of dependency on tourism has left the economy particularly dependent on seasonal climate conditions. Reliable transportation, water supply, energy, and communications infrastructure play a vital role in sustaining the Basin's economy. Damages to these assets and resulting disruptions that results can impose large costs on the economy.

Sensitivity and Exposure

Climate change is expected to increase repair and rehabilitation costs, shorten the rehabilitation life-cycle of infrastructure, and increase disruption of infrastructure networks. As detailed above, several climate change hazards threaten infrastructure, including flooding, higher-than-planned temperatures, wildfires, landslides, and avalanches. These events have potentially widespread economic consequences.

Table 3 summarizes the assessments of infrastructure by climate hazard. Cell shading is based on the average of Impact and Exposure scores generated for asset-climate hazard combinations in an earlier section of this vulnerability assessment. The darker the shading, the higher the risk that the climate hazard imposes on the infrastructure system. The assessment does not estimate damage quantitatively where it lacks data or would require modeling that is out of scope.

Table 3. Asset-climate hazard combinations, including those quantified and qualified

TRANSPORTATION SYSTEM ASSETS	Flooding Hazard	Temperature Hazard	Wildfire Hazard	Landslide Hazard	Avalanche Hazard
Major roads/evacuation routes (highways) and bridges	★	★	✓	✓	✓
Minor/residential roads and bridges	★	★			
Public transit systems and stations	★	★	✓	✓	
Airport grounds and facilities	★	★			
Bike paths and bridges	★	★		✓	
OTHER SYSTEM ASSETS	**Flooding Hazard**	**Temperature Hazard**	**Wildfire Hazard**	**Landslide Hazard**	**Avalanche Hazard**
Electricity: high-voltage lines, plants, substations	✓	✓	✓		
Fuels: Natural gas lines, gasoline refueling stations				✓	
Water and wastewater	✓		✓		
Broadcast and telecom transmission towers	✓		✓	✓	✓
Housing and buildings	★	✓	★	★	

Notes: Cell shading based on the average of Energetics Impact and Exposure scores. “Housing and buildings" shading is based on IEc assessment.

★ Economic risk assessed quantitatively

✓ Economic risk discussed qualitatively

* Addressed in Natural Environment section above

Implications

Without adaptation, climate change will broadly impact the Basin's built environment. This study estimates the economic impacts of climate change on the transportation network (including roads, airport runways, and bike trails), and then qualitatively describes potential impacts to other assets.

The Basin features an extensive network of roads spanning 3,228 miles, with paved and unpaved tertiary roads accounting for over 85 percent of the network. That network is critical to the Basin's economy as visitors to the Basin account for 42 percent of the 10 million vehicles that travel to the region every year (Bi-State Consultation 2018). Table 4 presents the historical and projected costs of temperature, precipitation, and flooding effects on road infrastructure (including both damages and delay costs), under the lowest and highest cost scenarios. Baseline costs of daily climatic events that exceed design thresholds are approximately $7 million annually. These costs increase universally under the climate models and emissions scenarios, with impacts ranging from approximately $11 million to $75 million by the end of the century. It is important to note that freeze-thaw cycles in the Basin are projected to decrease by between 14 and 40 percent by 2099. This would reduce the rate at which roads degrade, reducing projected damages by 5 to 10 percent, depending on climate change scenario. Winter road maintenance operations are also likely to decrease.

Table 4. Total historical and projected annual costs of climate change to road infrastructure in the Basin, under RCP 4.5 and RCP 8.5 Scenarios (millions $)

Scenario	2020-2039	2040-2059	2060-2079	2080-2099
Baseline*	$6.9	$6.9	$6.9	$6.9
Low Costs (RCP 4.5)	$7.8	$8.9	$8.3	$11.4
High Costs (RCP 8.5)	$15.4	$23.2	$48.4	$75.3

* The baseline transportation costs presented in the report do not include all costs spent on transportation (e.g., operations, maintenance, repair, and replacement), but rather only the costs of climatic events that exceed the design levels of infrastructure. For instance, if a culvert is designed to withstand a five-year flood event and a ten-year event occurs, the $6.9 million baseline would include the costs of this event. Defining the baseline this way allows for more readily estimating the incremental effects of climate change.

Over the full 2019 to 2099 period, annualized costs to the 1,820 miles of paved roads considered are as high as $8,400 per mile, which is more than double costs under a no-climate-change scenario, and 88 percent higher than the average projected costs of climate change impacts to paved roads across California. This means that climate change will greatly magnify expenditures on road maintenance, and place further pressures on communities such as the City of South Lake Tahoe. The City's entire General Fund expenditures for 2018 was $38.8 million, of which only 11 percent was designated for public works (City of South Lake Tahoe 2017).

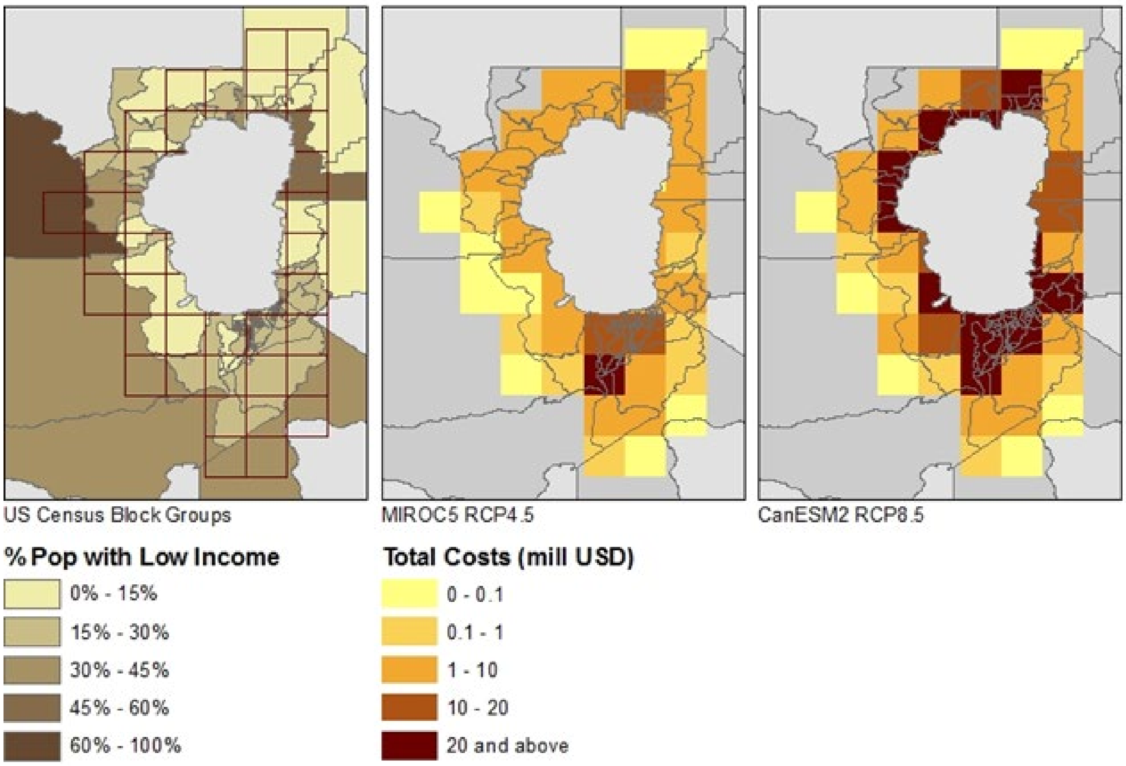


Figure 44. Percentage of low income population (left panel) and total 2019 to 2099 low- and high-end costs of climate change on transportation infrastructure (right panels)

Figure 44 presents these data spatially, comparing transportation impacts to the percent of the population in each census tract that falls below the federal low income threshold. Some of the lowest-income communities in South Lake Tahoe are located in zones with the most pronounced economic impacts. Along with rising housing costs, this adds to the economic vulnerability of low-wage workers. These areas may experience disproportionate impacts from climate change, such as diminished access to evacuation routes.

Although not quantified in this study, the following economic impacts of climate change on other key elements of the built environment may also be potentially significant.

Electricity distribution

Increased disruptions under climate change may cost the U.S. upwards of $1.5 trillion through 2100 (Larsen et al. 2018). For local reference, according to representative outage costs from Lawrence Berkeley Labs, impacts of an eight-hour outage in the City of South Lake Tahoe are nearly $400,000 (Sullivan et al. 2015). Even a modest increase in the frequency of outages would be costly.

Water supply and treatment

Climate change-induced flooding may cause underground wastewater conveyance systems to overflow, threatening lake and ecosystem water quality. If sufficiently severe, this can have an economic impact by reducing lake visitation. Wildfire can also severely threaten water supplies.

Communication network

Physical damage to communication network infrastructure through floods, landslides, avalanches, and wildfires, and resulting service disruptions, can cause economic damages. This is particularly true for extended disruptions due to equipment damage.

Recreational trails

Construction costs of ten-foot wide asphalt bike paths in the Basin can be as high as $8 million per mile. Significant damages to this resource due to increased flooding and landslides would strain local jurisdiction budgets within the Basin.

Housing and buildings

Under climate change, air conditioning costs could increase significantly. For example, between 1961 and 1990, the General Creek-Frontal Lake Tahoe Watershed experienced an average of four cooling degree days annually (CDDs, the number of degrees that a day’s average temperature is above 65 degrees Fahrenheit). Under RCP8.5, CDDs are projected to increase to 81 CDDs by 2050 and 340 CDDs by 2090, signifying a significant increase in cooling costs (Cal-Adapt, 2019).

Properties are also at risk of increased flooding and increased wildfire. Maximum daily streamflow and runoff are expected to increase significantly in the watersheds around Tahoe Pines and Timberland. As seen in Figure 45, valuable property currently surrounds the 100-year floodplain. If this footprint were to expand in future climates, valuable property could be at risk. In terms of wildfire risk, as seen in Table 5, there is a significant chance for losses in Placer and El Dorado counties, which currently have $911 million and $1.2 billion of property, respectively, in areas with a high to extreme threat for wildfire.

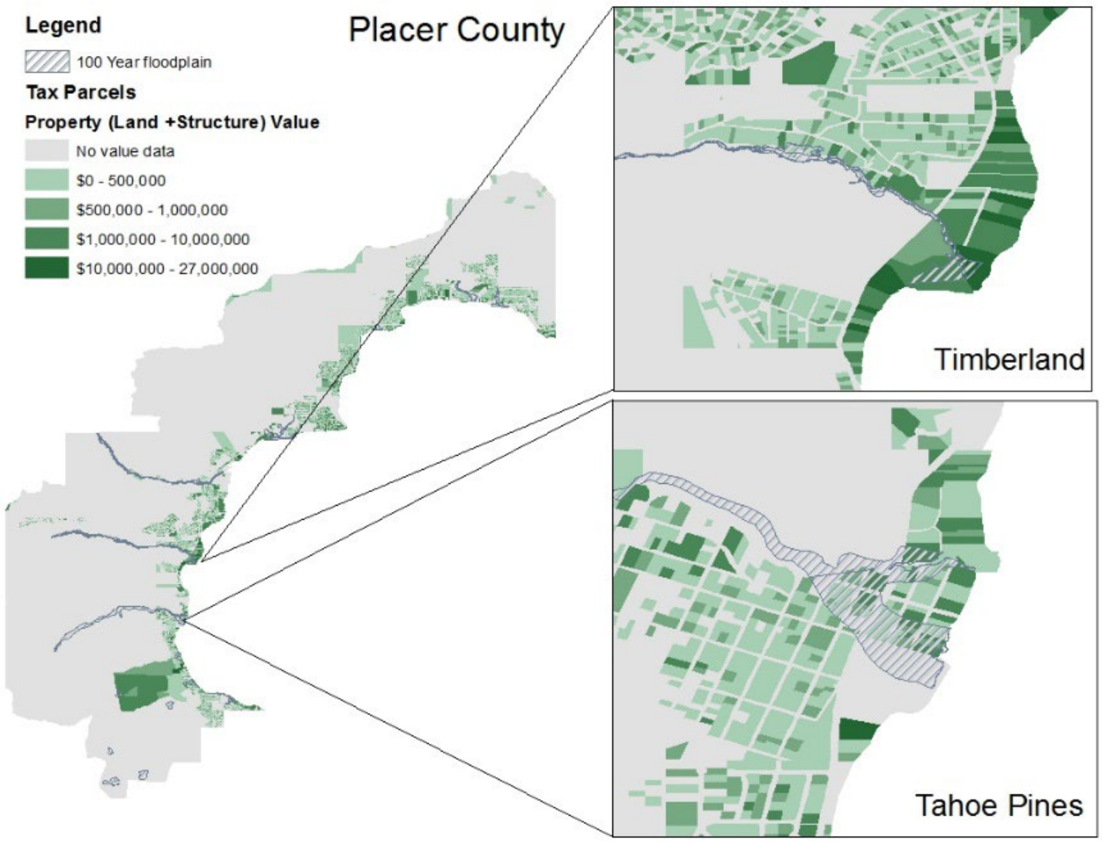


Figure 45. 100 year floodplain and surrounding property values: Placer County

Table 5. Fire risk level for Basin property values, by county

County	Very Very Low Fire Threat Level	Very Low Fire Threat Level	Low Fire Threat Level	Low-Moderate Fire Threat Level	Moderate Fire Threat Level	Moderate-High Fire Threat Level	High Fire Threat Level	Very High Fire Threat Level	Extreme Fire Threat Level	Total Assessed Property Value in Basin (millions)
Douglas	0%	9%	6%	14%	19%	32%	19%	0%	0%	$1,066
Carson	35%	56%	3%	3%	2%	1%	1%	0%	0%	$71
Washoe	1%	4%	3%	18%	39%	20%	14%	1%	0%	$1,579
Placer	4%	15%	5%	12%	23%	23%	11%	5%	2%	$5,093
El Dorado	3%	21%	7%	13%	16%	13%	15%	9%	3%	$4,835
TOTAL	$401	$2,006	$706	$1,663	$2,777	$2,469	$1,701	$682	$238	$12,644

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APPENDIX A

Example Vulnerability Scoring Matrix

Climate Change Vulnerability Assessment - Sensitivity, Exposure, and Adaptive Capacity Scoring Matrix

Issue Questions	Response/Score
Resource Categorization and Impacts	
Resource/Sub-Resource?	
Ecosystem service provided by resource?[1]	
What are this resource's connections/linkages to other resources?[2]	
What are the potential climate change effects that could impact the resource?	
Sensitivity[3] and Exposure[4]	
How exposed is the resource to changing climate conditions? (1-5)[5]	
What is the resource's current degree of stress? (1-5)[6]	
How sensitive is the resource to changing climate conditions? (1-5)[7]	
Does the species/resource use or inhabit multiple habitats or environments? (1-5)[8]	
Conclusion (Average)	
Adaptive Capacity[9]	
How quickly can the resource adapt to changing climate conditions? (1-5)[10]	
To what extent are there plans already in place to protect/improve the resource/species? (1-5)[11]	
How much intrinsic ability/capacity does the resource have to adapt to changing climate conditions? (1-5)[12]	
Generally, how resilient or adaptable is the resource? (1-5)[13]	
Conclusion (Average)	

Notes

[1] The Millennium Ecosystem Assessment (2005) defines *Ecosystem Services* as benefits people obtain from ecosystems and distinguishes four categories of ecosystem services: Provisioning, Supporting, Cultural and Regulating. See Millennium Ecosystem Assessment at https://www.millenniumassessment.org/documents/document.765.aspx.pdf for more information on the types and categories of ecosystem services.

[2] How does this resource's function affect other resources/species? What resources/factors does the resource depend on to function?

[3] *Sensitivity* is the degree to which a system will respond to a given change in climate, including beneficial and harmful effects).

[4] *Exposure* is a measure of how much a change in climate and associated problems a species or system is likely to experience.

[5] 1 = little/no exposure; 5 = high exposure

These factors may include: temperature, precipitation, climatic water deficit (i.e., soil moisture), wildfire, snowpack, runoff, timing of flows, low flows, high flows, and stream temperature.

[6] 1 = thriving; 5 = high stress, declining

Ecological stressors are physical, chemical, and biological factors that impact the condition and integrity of ecosystems and can change the trajectories of species and ecosystems. Stressors can be natural (fire, storms, insect outbreaks), or anthropogenic (e.g., climate change, fire, energy development). Climate change impacts can be a tipping point for some resources or species that are currently in decline due to existing conditions.

[7] 1 = no/little sensitivity; 5= high sensitivity

To what degree will the resource/species be affected, either adversely or beneficially, by climate variability or change? Low sensitivity represents the scenario that a resource will not be significantly impacted by climate change, whereas high sensitivity represents the scenario where the resource/species will be significantly impacted.

[8] 1 = widely dispersed and inhabits numerous types of environments; 5= limited geographic range and is located in one type of environment

A resource/species that can inhabit multiple environments or is widely dispersed has lower sensitivity to climate change than a resource that is limited in its geographic range and ability to inhabit a range of environments. Can the resource/species adapt latitudinally and longitudinally?

[9] *Adaptive Capacity* refers to the degree to which adjustments in practices, processes, or structures can moderate or offset the potential for damage or take advantage of opportunities created by a given change in climate, independent of management interventions.

[10] 1 = no/very low rate of adaptation; 5 = rapid rate of adaptation

Can the resource adapt at the same pace as changes to its environment?

[11] 1 = no plans; 5 = highly protective conservation/management plans in place

Humans have the potential to intervene in ways that reduce the impacts of climate change on particular resources/species. If a resource/species is being actively managed for protection or conservation, humans are creating opportunity for the resource/species to adapt to climate change. For example, if a species is listed as threatened or endangered, it can provide opportunities for implementing specific management measures likely to help populations persist.

[12] 1 = no/little adaptability; 5 = highly adaptive

Some resources/species will be better able to adapt evolutionarily or express varying traits in response to environmental variation. Does the resource possess unique qualities to adapt or evolve?

[13] 1 = not resilient; 5 = very resilient

High resilience/adaptability represents the capacity of a resource/species to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks. Low resilience represents

Appendix B

Technical Memos

Available at https://tahoe.ca.gov/programs/climate-change/

Lake Tahoe Vulnerability Assessment, Geoffrey Schladow, PhD, University of California, Davis

Aquatic Resources Vulnerability Assessment, Sudeep Chandra, PhD, University of Nevada, Reno

Watershed Hydrology & Streamflow Vulnerability Assessment, Alan Heyvaert, PhD, Desert Research Institute (DRI)

High-Elevation Groundwater Vulnerability Assessment, Alan Heyvaert, PhD, DRI

Low-Elevation Groundwater Vulnerability Assessment, Alan Heyvaert, PhD, DRI

Soil Moisture & Infiltration Vulnerability Assessment, Alan Heyvaert, PhD, DRI

Forest Biological Diversity Vulnerability Assessment, 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

Forest Ecosystem Dynamics Vulnerability Assessment, Patricia Manley, PhD, PSW; Patricia Maloney, PhD, University of California at Davis, Karen Pope, PhD, PSW; Peter Stine, PhD, PSW

Riparian and Aspen Ecosystems Vulnerability Assessment, Patricia Manley, PhD, PSW; Patricia Maloney, PhD, University of California at Davis, Karen Pope, PhD, PSW; Peter Stine, PhD, PSW

Meadow Ecosystems Vulnerability Assessment, Patricia Manley, PhD, PSW; Patricia Maloney, PhD, University of California at Davis, Karen Pope, PhD, PSW; Peter Stine, PhD, PSW

Wildlife Connectivity Vulnerability Assessment, Peter Stine, PhD and Patricia Manley, PhD; PSW

Public Health Vulnerability Assessment, Sam Evans, Tim Holland, Matthew Potts (University of California, Berkeley)

Washoe Cultural Resources Vulnerability Assessment, Jonathan Long, PhD, PSW

Lake Tahoe Surface Elevation Projections, Shane Coors, Precision Water Resources Engineering

Recreation Resources Vulnerability Assessment, Patricia Winter, PhD, PSW

Lake Tahoe Basin Infrastructure Vulnerability Assessment, Patricia Winter, PhD, PSW

Integrated Vulnerability Assessment of
Climate Change in the Lake Tahoe Basin

2020

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