Adapting to Climate Change Impacts on the Colorado River in Grand Canyon National Park

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Abstract

Climate change is likely to have impacts on the Colorado River and the surrounding ecosystems and communities in Grand Canyon National Park. While the National Park Service has a variety of plans to manage the Colorado River and the Grand Canyon, these plans fail to address direct adaptation strategies to climate impacts such as drought and streamflow impairment, water quality reduction due to wildfires and extreme heat, and ecosystem mortality events. The depletion of the river over time and changes in streamflow have become a key area of concern due to increasing temperatures and changes in precipitation. Furthermore, increased events such as wildfires and heatwaves are likely to reduce the water quality of the river by aggravating runoff and soil erosion. Climate change will also impact the ecosystem mortality of native fish, birds, and other organisms. This paper highlights key adaptation strategies that address each of these three impacts and improve the resilience of the ecosystems of the Grand Canyon through strategies such as reducing water usage, removing legacy sediment, reducing hazardous fuels, determining optimal population sizes for ecosystems, ensuring habitat connectivity, and more.

Plain Language Summary

The Grand Canyon National Park on the Colorado River has been greatly impacted by climate change impacts, including rising temperatures and altered weather patterns across the region. These impacts have created several negative consequences for the ecosystem and surrounding communities in the Grand Canyon, including drought, reduced water quality, and loss of native biodiversity. Though multiple plans have been developed in the Colorado River Basin to manage climate risks, none have adequately prepared the Grand Canyon National Park for successful long-term adaptive management. This paper proposes comprehensive action on local/regional scales so that the National Park System can adapt to the negative consequences of climate change. We assess how these potential climate adaptation strategies will benefit the region’s ecosystems and communities, and identify stakeholders that can aid in enacting these plans in the Colorado River Basin.

Introduction

The Colorado River is one of North America's longest and most important rivers, flowing 1450 miles from Poudre Pass in Rocky Mountain National Park in Colorado, all the way to the Gulf of California in Mexico. The Colorado River passes through seven states in the United States (WY, UT, CO, NM, AZ, NV, and CA) and two states in Mexico (Sonora and Baja California). Among the 1450 miles of river, 277 of them pass through Arizona's Grand Canyon National Park, carving its magnificent landscape over millions of years. The Grand Canyon is situated between Lake Powell and Lake Mead in the Colorado River's path (American Rivers Staff 2016).

In addition to the Colorado River's beauty, it is an economically important part of the region. The Colorado River sustains $1.4 trillion worth of economic activity every year – at least half of the GDP of western states including Arizona – and 16 million jobs in the U.S. The river's economic impact is closely linked to real estate, healthcare, and retail (Nature Conservancy Staff 2022). Today, the river's water levels are at all-time lows due to significant withdrawals from the river, primarily for commercial and agricultural use (American Rivers Staff 2016).

The Grand Canyon region has been already affected by climate change in several ways. The existing scientific literature on the Colorado River Basin suggests that increasing temperatures and persistent drought conditions are lowering water levels in the Colorado River. One study projects a reduction in flow of 10-30% by 2050 (American Rivers Staff 2016), while another predicts the flow to be cut by 50% by 2100 (Goldfarb 2021). This, among many other daunting effects of climate change, could pose significant threats to local ecosystems and native species living within them.

In the Colorado River, there have been significant declines in the populations of many of the native species, including the humpback chub, razorback sucker, and speckled dace (Go Grand Canyon Staff 2022). The Colorado River's invasive species, like the walleye, northern pike, and smallmouth bass, could become more widespread as the river warms due to climate change (Goldfarb 2021). On top of the issues of decreased water levels and changes in native species' and invasive species' populations, climate change will affect weather patterns and precipitation, and therefore vegetation and soils, among many other ecological systems.

The aim of this project is to thoroughly understand the impacts that climate change is already having –and will have in the future– on the Colorado River and the surrounding ecosystems in the Grand Canyon. It is imperative to understand how the water supply crisis is impacting ecosystems and local economies, and how policymakers and the National Park System should address these issues. We will investigate the current climate adaptation measures being taken in the Grand Canyon region of the Colorado River Basin, and explore new methods of mitigating localized climate impacts.

The National Park Service (NPS) has implemented various plans to address climate impacts in the Colorado River Basin: the 2006 Colorado River Management Plan (CRMP), the 1995 Grand Canyon General Management Plan (GCGMP), the Glen Canyon Dam Adaptive Management Program (GCDAMP), and the Grand Canyon National Park Climate Action Plan. (GCNPCAP). The 2006 CRMP is a visitor use management plan that discusses action to conserve park resources, improve visitors experience, and enhance river running recreational opportunities. The GCGMP provides management guidance for the entirety of the Grand Canyon but also discusses management of water resources. The plan states that "water withdrawals needed for administrative use will be limited to current levels and will be done in a way to minimize impacts to park resources" (National Park Service 1995). It also states that the NPS will protect park water rights when necessary. GCDAMP describes the current state of the Colorado River Ecosystem in the Grand Canyon and evaluates important aspects of the Colorado River ecosystem, such as fish of the Grand Canyon, climate fluctuations, water quality, aquatic ecology, and riparian vegetation and wildlife (National Park Service 1995). The GCNPCAP discusses mitigation of climate change, some plans for adaptation, and scenario based planning.

Existing research on extreme events that may impact the Colorado River Basin supports the adaptive management system currently used by the NPS. The extremes in temperature and precipitation, which are likely to become more common with climate change, are associated with abnormal weather conditions in the Colorado River. An article published in the *Journal of the American Water Resources Association (JAWRA)* looks at the impacts of identified extreme weather events and recent examples that have affected the Colorado River Basin (McCoy et al. 2022). The source identifies the link between climate change, extreme events, and impacts on the Colorado River Basin while also demonstrating the importance of creating adaptive management plans that can adjust to unexpected events. The authors identify climate change trends such as hotter periods, less precipitation, streamflow declines, etc. and highlight recent examples of these events in the Colorado Basin.

Other studies review the impacts of climate change and management scenarios on ecosystems and communities. An article from the *Global Change Biology* journal examines how changes in climate will interact with other stressors to threaten aquatic ecosystems and their biota in the Colorado River Basin (Roberts et al. 2013). The source finds that current restricted distribution of native Colorado River Cutthroat Trout (CRCT) reduces the potential thermal impacts of climate change, but fragmentation increases their susceptibility to catastrophic stochastic events like extreme weather. It also recommends that CRCT conservation efforts should focus on preventing further loss of habitat. However, this study does not address the link between climate change and the greater aquatic ecosystem of the Colorado River. This gap in their research presents challenges in our understanding of climate impacts on the river's biodiversity, requiring a more holistic approach for adaptation management.

Another important area of concern is local preference for management scenarios and community dependence on water resources. A study in the *Land Use Policy* journal found that in communities in Biscay, Spain, local populations valued improving water quality above all (Castillo-Eguzkitza et al. 2019). The results suggest that allocating funding that improves land water use management maximizes social well-being of local communities and will be financially supported by these regions. Fleck and Castle evaluated past and present Colorado River governance and management and how it has impacted communities, and found that communities impacted by reductions in water use have been successful in adapting to smaller supplies (Fleck & Castle 2021). Furthermore, they recommend that the water rights and claims of indigenous communities must be incorporated into river management decision-making (Fleck & Castle 2021).

Although the 2006 CRMP investigates various aspects of river conservation (e.g. management direction, education and outreach, river management responsibilities, etc.), it contains deficiencies that require more research and attention from the National Park Service. First, the document fails to address the negative impacts of drought on the stream flow of the Colorado River Basin. Although the current plan talks about the impacts of climate change on the river's biodiversity and aquatic species like humpback chub, it doesn't mention how climate change might further impact the river's aquatic ecosystems and local communities. Second, the plan lacks specific long-term goals shaping the future orientation of Colorado River conservation. The current document lists the overarching goal of adaptive management of the river, "that a resource condition meets standards established by resource managers, and that the trend is stable or improving," which is vague and doesn't include any statistics (National Park Service 2006). By constructing detailed and realistic long-term goals, the NPS can accelerate and motivate the mitigation of climate change impacts on the Colorado River. Third, the plan lacks a framework that evaluates the outcomes of current river conservation practices. By assessing how each climate change impact on the river is dealt with, the NPS can acquire a clearer idea of how to improve their management plan.

In 2010, Grand Canyon published a Climate Change Action Plan to address mitigation and adaptation to climate change. However, the plan primarily plans for mitigating climate change through reducing greenhouse gas emissions of the park. While the action plan highlights a few climate adaptation actions for shorter-term and long-term, these strategies are broad and vague. Furthermore, while the plan lists specific impacts, it fails to discuss adaptation strategies for these particular impacts on the Grand Canyon.

Given the limitations of the National Park System's current policies for climate change management on the Colorado River, our research will grant significant insights for relevant stakeholders: the Grand Canyon National Park, its surrounding communities, and other national and state parks. This research paper will contribute valuable new understandings of the localized effects of climate change in the Grand Canyon, as well as proposed joint action to be taken by the National Park System and other communities that rely on the Colorado River. This study will also be relevant to other governing bodies that are tasked with protecting wilderness areas that are being impacted by climate impacts now and in the future. This study explores these impacts as they relate to both land and aquatic ecosystems in the Grand Canyon and the Colorado River. We seek to inform our reader of different climate adaptation strategies that can be adopted by the National Park System in response to anthropogenic environmental change. We will evaluate such actions by their effectiveness in minimizing ecological and socio-economic damages to the region, cost efficiency, time scales of action, and other relevant criteria.

Drought and Streamflow Impairment

Some of the most pressing consequences of climate change facing the Colorado River Basin are drought and altered streamflow on the Colorado River. Within the last 20 years, the Colorado River's annual streamflows have fallen 19% below the 20th century average, marking the worst drought conditions ever observed in the Colorado River Basin (Udall & Overpeck 2017). Predictions from climate scientists estimate future declines in streamflow to fall as low as -35% by the mid-21st century (Udall & Overpeck 2017). These impacts are primarily caused by rising annual temperatures, triggered by unabated greenhouse gas emissions and global warming (Kopytkovskiy et al. 2015).

Climate scientists have debated the effect of rising temperatures on average precipitation in the area. The U.S. government's assessments have implied that minimal streamflow change will be observed in the Colorado River Basin due to offsets created by increased precipitation (Reclamation 2016). Indeed, increased surface temperatures can raise the saturation vapor pressure of Earth's atmosphere, leading to higher moisture content and thus greater precipitation rates (Gorman & Schneider 2009). However, several climate science studies from the last 25 years have cautioned that global warming will likely deplete the river over time (Udall & Overpeck 2017). The extent and source of the variations have differed among these studies. Researchers for the Journal of Hydrology generated climate change models to show how water resources in the Colorado River Basin will be affected in the future, and found differential impacts by elevation: higher elevations are projected to receive 74% more precipitation, while lower elevations are expected to have a 60% decline (Kopytkovskiy et al. 2015). The researchers identify that a significant mechanism leading to greater streamflows at higher elevations is snowmelt due to warming temperatures (Kopytkovskiy et al. 2015).

Water use in the Colorado River Basin has been heavily impacted by climate change effects. The river is a critical water supply for nine states and two nations in Western North America (Fleck & Castle 2021). The Colorado River's streamflow has decreased greatly during the 21st century due to increased temperatures and evaporation, but has also been compounded by overallocation (Fleck & Castle 2021). Currently, water allocation is dictated by regional governance and lacks a federalist structure that can impose basin-scale solutions (Gerlack et al. 2014). This fragmented governance system creates a "complex web of disjointed authorities and institutions… with no single venue to deal comprehensively with Colorado River Basin issues" (Karambelkar & Gerlak 2020). Additionally, several indigenous tribes in the area lack water rights that ensure fair use for these groups, which will likely exacerbate problems of water allocation in the coming years (Fleck & Castle 2021). As the volume of water in the Colorado River decreases with rising temperatures, the difficulties of establishing water use rights becomes even more of a challenge for those that manage water resources in the Colorado River Basin.

The groundwater supply in the Grand Canyon region is of critical importance to those living in the region, especially due to limited access to the river's surface waters. Groundwater supplies "nearly all water needs of residents" as well as the 6 million tourists that visit the region each year (Tillman et al. 2020). Climate researchers with the U.S. Geological Survey used climate projection models and Soil Water Balance groundwater infiltration simulations to model expected changes to the groundwater supply in future decades. They showed that the combined impacts of increased temperatures and reduced soil moisture will lead to less water available for groundwater infiltration and aquifer recharge (Tillman et al. 2020). These effects are made complicated by the uncertain time scales on which they will occur, as well as the uneven changes in groundwater infiltration across the region (Tillman et al. 2020). Therefore, it is imperative that water resource management in the region anticipates these future changes well before they may actually occur.

Changes in streamflow on the Colorado River have become a great concern for those invested in hydropower production on the river. Hydropower is generated by using the power of moving water to produce electricity, most commonly as it spills over large dams. Therefore, hydropower inherently depends on the river's streamflow for energy production. Climate change's impacts have already taken their toll on hydroelectricity production in the region: the U.S. Bureau of Reclamation predicted a nearly 50% chance that Lake Powell's water levels would drop below the target level for safe hydropower generation by 2023 (Fleck & Castle 2021). While many of the reservoirs on the Colorado River reside at high elevations, meaning they have high hydropower production potential; however, due to severe drying in summer months, little to no hydroelectricity can be generated during these periods of drought (Kopytkovskiy et al. 2015). Due to expected reductions in water volume on the Colorado River, adaptation strategies must consider how best these reservoirs can be maintained so that hydropower generation is still possible in the future.

Water Quality Reduced Due to Wildfires and Heatwaves

Another climate change impact suffered by the Colorado River is reduced water quality resulting from wildfires and heat waves. When soil burns due to wildfires, harmful substances (e.g. lead, mercury, cadmium) contained in it are released. When they enter the river at high concentrations, its mountain collection system - which connects to the water systems of towns and farms - risks being impaired (Smith 2021). The impairment negatively affects the water supplies of municipalities.

Colorado's Front Ranges slopes impacted by wildfires experience erosion following thunderstorms or summer rains. This contaminates the urban water supplies with metals, waste, and dissolved nutrients. The level of erosion depends on how fast a wildfire advances. A wildfire traveling fast is unlikely to cause massive destruction of forests and soil or erosion of slopes. On the other hand, a wildfire moving slowly burns the area significantly, generating ash and releasing nutrients from the soil's organic layer. Moreover, it aggravates runoff and erosion as chemicals from the leaves evaporate and accumulate in the soil, by which the soil becomes water resistant. Contaminated river water following erosion obstructs pipes too, inducing algal blooms and clouds in the river's reservoirs and impairing their water (Fountain 2021).

Heat waves are observed when temperatures of an area rise above its past averages for two or more days. The summer months of 2020 marked one of the warmest and driest periods for the Grand Canyon National Park. In August 2020, the average temperature of Northern Arizona (where the Grand Canyon National park is located) was 68.8℉, 4.6℉ higher than the usual temperature; monthly precipitation was 0.31 inches, 10% of normal precipitation (National Weather Service 2020). As for the Grand Canyon National Park's mean annual temperature, it is expected to rise by 4-5℉ around 2050 and by 5-8℉ in 2099 from its 1971-1999 average value (Table 1) (Fisichelli 2013). These heat wave conditions, intensified by global warming, are destroying the Colorado River Basin's stream flows as the earth's surface becomes drier and plants intake more water (James 2021). They could harm the river's water quality by inducing drought, hot weather, and wildfires in the area (McCoy et al. 2022).

The adverse effects of heat waves on the Colorado River's water quality are evident in historical data. The river's discharge is the total volume of water traveling through a river at any given site (Internet Geography 2022). From 1980 to 2021, the river's annual mean discharge (ft^3/sec) decreased from 15,760 to 11,970 (USGS Staff 2022). Low river discharge, indicative of hydrological droughts, could worsen water pollution by reducing the amount of water available for diluting industrial and nonpoint source wastes. This increases the concentration of contaminants in the river, reducing its water quality (EPA 2022). Moreover, in April 2019, the river's water temperature (℃) was 12.5℃, a 2.5℃ increase from April 1980 (USGS Staff 2022). Warmer river temperatures could quicken chemical events in nature, releasing excessive nutrients into water and degrading its quality. Also, higher river temperatures could alter water circulation in the river, consequently its nutrient and salinity levels (EPA 2022).

Temperature Difference from 1971-1999

	Greenhouse Gas Emissions Scenario		Confidence in Projection
Years	Low (B1)	High A2	
2021-2050	+3 °F	+3 °F	High
2041-2070	+4 °F	+5 °F	High
2070-2099	+5 °F	+8 °F	High

Table 1 (Fisichelli, Nicholas. 2013)

Ecosystem Mortality

Another massive component of the impact of climate change on Grand Canyon National Park (GCNP) is ecosystem mortality. The entire ecosystem in GCNP will be affected by climate change, including the soil and vegetation, the fish in the river, the birds, and other organisms.

There is consensus among GCNP climate models that the pinyon-juniper woodland ecosystem will experience increases in mean monthly and annual temperatures: an average increase of 2.5ºC in the short-term, and 5.0°C in the long-term (USGS 2020). These models also predict decreases in soil water availability: by 2100, "average spring soil water potential (SWP) is expected to drop below -3.0MPa, indicating conditions of extreme water scarcity" (USGS 2020).

The soil will become dry earlier in the spring (both in the short-term and long-term), which will decrease soil moisture during the spring growing season and will therefore affect the plant species that rely on certain soil moisture levels. Declines in SWP in the fall, winter, and spring are expected, with the spring actually becoming more dry than the summer. This is illustrated in Figure 3 below. Furthermore, drought conditions are expected to increase in length in GCNP. Currently, the drought period begins in mid-April and lasts until mid-July, but increasing temperatures will cause an earlier start and a later end, which can be seen in Figure 4 below (USGS 2020).

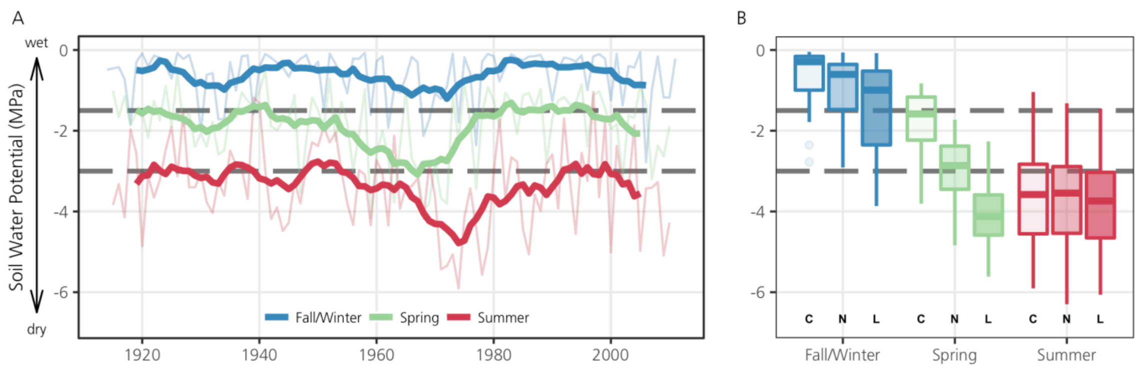

Figure 3 (Andrews et al. 2020)

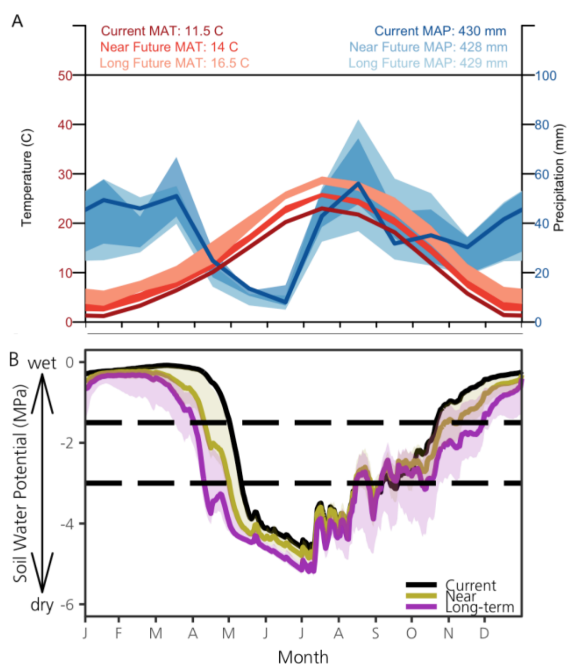

Figure 4 (Andrews et al. 2020)

As the climate in the GCNP warms, and the river flows and flood frequency decrease, the vegetation that dominates this region will undergo a transition from species that require more water – such as native willows, rushes and cattails – towards species that are more drought-resistant, such as mesquite, tamarisk and desert grasses (McCoy-Sulentic et al. 2017)

In terms of climate change and its impact on fish in GCNP, in 2004, there was a joint effort by the Grand Canyon Trust and Earthjustice to sue the federal government to force action to protect the humpback chub. For over four million years, this native fish species has thrived in the muddy waters of the Colorado River, with its iconic rudder-like hump that makes it uniquely suited for the turbulence present in the canyons of the Colorado River. However, due to the presence of the dams on the Colorado River, the humpback chub as a species – and the ecosystems they inhabit, as a whole – are under threat (Earthjustice 2006)).

For the Grand Canyon's portion of the Colorado River, the Glen Canyon Dam just upstream has turned the naturally-roaring river calm. This has led to ecosystem changes that have rendered some native species extinct already – with four out of eight native fish species having fallen victim so far – and others like the humpback chub struggling to survive. "In just 13 years, the humpback chub in the Grand Canyon have declined by two-thirds, from 10,500 in 1989 to 3,500 in 2002" (Earthjustice 2006).

One study found that native Colorado River cutthroat trout (CRCT) are relegated to the Upper Colorado River Basin due to nonnative trout invasions and habitat loss. The authors found that the current restricted distribution of CRCT populations due to the high degree of fragmentation increases their susceptibility to catastrophic stochastic (random) events. What's more, the authors predict that combining fragmentation with the effects of harmful stochastic events presents a greater threat to CRCT populations than the warming climate. That's because, given the existing problems of past nonnative trout invasions and habitat loss, CRCT populations have been pushed to "high-elevation stream fragments that are buffered from the potential consequences of warming, but at risk of extirpation from stochastic events" (Roberts 2013).

Moving on from fish, birds can tell us a lot about climate change in an ecosystem, since they have very high mobility and are very noticeable. In the face of climate change, some bird species are harmed in a given location, while others are helped; this means some bird species may be due for extirpation (local extinction), and some for new colonization. In regards to Grand Canyon National Park (GCNP), bird communities are expected to undergo greater changes in the event of the high-emissions scenario as opposed to the low-emissions one, as shown in Figure 1 (Schuurman and Wu 2018).

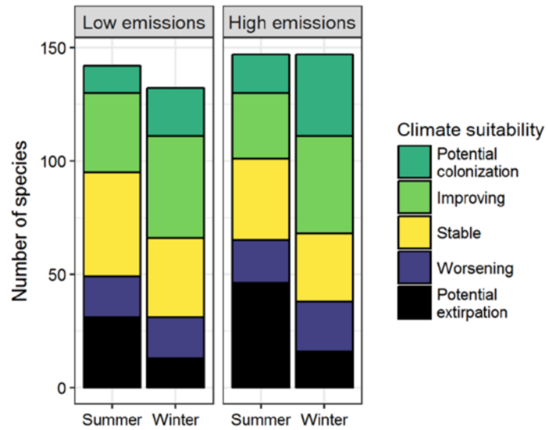

Figure 12: Projected changes in climate suitability for birds at GCNP, by emissions pathway and season (Schuurman and Wu 2018)

For the bird species currently present at GCNP, summer climate suitability given the high-emissions pathway is likely to be more suitable for 29, equally suitable for 36, less suitable for 19, and totally unsuitable for 46 – which means possible extirpation for those species. In addition, this scenario involves summer climate suitability for 17 new species – ones that are not currently present in GCNP – which opens the possibility to new colonization (Schuurman and Wu 2018).

For the winter climate suitability given the high emissions pathway, conditions will likely be more suitable for 43 species, equally suitable for 30, less suitable for 22, and totally unsuitable for 16 – which means possible extirpation. There are 36 possible new colonizations for bird species not currently present but that are likely to have suitable climate conditions in this scenario (Schuurman and Wu 2018).

Comparing these two situations, the winter and the summer under the high-emissions scenario, it's clear that the summer is projected to be much more unsuitable for the current species inhabiting the GCNP, with 46 species facing possible extinction in the summer compared to only 16 in the winter. Projections for bird species turnover for GCNP between now and 2050 is 0.22 for the summer and 0.17 for the winter (35th% and 22nd%, respectively) under the high-emissions pathway. For the low-emissions pathway, these values drop to 0.15 for the summer and 0.10 for the winter (Schuurman and Wu 2018).

GCNP is now home to, or will likely become home to, 22 highly climate-sensitive species, which means over 50% of their range will become unsuitable due to climate change by 2050. Current projections show that GCNP may be a key refuge for 11 of these species, while 11 might be extirpated from GCNP, by 2050 (Schuurman and Wu 2018).

Gaps in Adaptation

The 2006 Colorado River Management Plan (CRMP)

The 2006 Colorado River Management Plan (CRMP) investigates various aspects of river conservation of the Colorado River in Grand Canyon National Park. The management plan, which is first and foremost a visitor use plan, specifies actions to conserve park resources and visitor experiences. The plan highlights adaptive management as crucial to providing feedback to park management and allowing activity adjustment as conditions arise. The management plan lacks recognition of how climate change impacts such as drought, reduced streamflow, water quality, and ecosystem mortality events might shape visitor use and experience of the Colorado River. It also lacks long-term goals shaping the future of Colorado River conservation (National Park Service 2006).

The 1995 Grand Canyon General Management Plan (GCGMP)

The 1995 Grand Canyon General Management Plan (GCGMP) provides management guidance for the entirety of the Grand Canyon, including management plans for the water resources of the Grand Canyon which are important to streamflow and water quality. The plan identifies management objectives that are relevant for the Colorado River for 1) natural and cultural resources and 2) wilderness and wild river. GCGMP identifies preserving natural spring and stream flows and water quality as an objective. It aims to only withdraw “the minimum water necessary to meet park purposes” (National Park Service 1995). Furthermore, it identifies protecting and preserving the Colorado River corridor as a key objective. It recommends designating eligible segments of the Colorado River and its tributaries as part of the national wild and scenic rivers system. In terms of management guidelines, the plan states that flows must be managed to “maintain the natural values of the river corridor” (National Park Service 1995). Furthermore, the plan states that water withdrawals for administrative use should not exceed current levels and should minimize impacts to park resources. While these management plans for water resources are important, they fail to address adaptation options to climate change impacts on drought, reduced stream flows, and water quality (National Park Service 1995).

There are also provisions in the GCGMP for dealing with fires. The plan states that the Park Service will restore the nature of fire within park ecosystems and within constraints of the park's Fire Management Plan. Furthermore, it highlights the need of additional studies and surveys on "the effects of fire exclusion and prescribed fire on park wildlife and the representative vegetation communities" (National Park Service 1995). It states that the Fire Management plan will be updated to address the restoration of the natural fire regime in the area (National Park Service 1995).

Similarly, the GCGMP highlights objectives and management plans specific to the ecosystems of the Grand Canyon and Colorado River. However, these plans are broad and do not address ecosystem mortality events impacted by climate change. The management plan highlights developing and implementing an ecosystem approach to managing threatened and endangered species. It proposes the development of an ecosystem research program "based on a baseline inventory and long-term monitoring program" (National Park Service 1995). No objectives are outlined for managing climate change within this plan. Furthermore, there are no specifications for dealing with ecosystem mortality events (National Park Service 1995).

Grand Canyon National Park Climate Action Plan (GCNPCAP)

As a member of Climate Friendly Parks, Grand Canyon National Park has published a Climate Action Plan that addresses mitigation and adaptation to climate change. Grand Canyon National Park Climate Action Plan (GCNPCAP) highlights climate adaptation actions for within the next 1-2 years and within the next 5 years. Within 1-2 years, Grand Canyon National Park plans to incorporate climate change into all planning efforts and documents. In addition, it has plans to coordinate with other agencies and partners to participate in landscape and regional scale resource management efforts and consult on issues such as fire management and cultural/historical sites. The plan states it will evaluate its climate change specific Citizen Science program. The NPS also plans to continue vegetation restoration and incorporate Common Garden plots research. The plan recommends accessing scientific and technical expertise through engaging with the Cooperative Ecosystem Studies Units (CESU) National Network (Martin 2010).

Within 5 years, the Grand Canyon plans to create a Grand Canyon adaptation plan/strategy and participate in future scenario planning and other workshops on impacts. Through conducting vulnerability assessments, documenting conditions, evaluating and compiling data, and making this available to the public and partners, Grand Canyon National Park hopes to adapt to climate change (Martin 2010). So far, no Grand Canyon adaptation plan has been created.

Grand Canyon National Park Climate Action Plan plans for adaptation and impacts for a three different climate scenarios: A) "Current unusual becomes normal" B) "On the road to Sonoran conditions" and C) "The New Sahara Desert" (Martin 2010). According to the climate scenarios considered the Grand Canyon National Park's Climate Action Plan, ecological conditions vary by scenarios. In Scenario A, ecological conditions include more summertime stress on water resources, more intense hydrologic cycle, patches of tree mortality, and fire mortality. Scenario B is characterized by an intensified hydrologic cycle, more intense forest die-off, and accelerating fire regime. Finally, Scenario C is marked by conditions such as permanent drought, decreased precipitation, intensified hydrologic cycle, wholesale forest die-offs, and invasive plants dominating (Martin 2010). While these scenarios are notable for identifying specific climate change impacts, the action plan fails to discuss how it will adapt to them.

General Adaptation Recommendations

Updating scenario-based planning is necessary to better capture the climate impacts on the National Park. Scenario planning is a tool adapted by the National Park Service that "offers a framework for working with uncertainty and preparing for a wide range of plausible future conditions" (National Park Service 2022). Unlike forecast based planning, which uses predictions of a single future, scenario based planning includes a set of scenarios to capture a range of conditions. Currently, the Grand Canyon Climate Action Plan includes only three scenarios and does not include any adaptation strategy for specific impacts like drought, decreased precipitation, and forest die-off. Compiling a list of specific strategies to adapt to different impacts is crucial to improving the Grand Canyon's readiness and response. The scenario planning could also better expand on how climate impacts might directly affect species and ecosystems in the Grand Canyon. The scenario planning of the Grand Canyon's Climate Action Plan could also be improved by collecting data on conditions like temperature and stream flow. Furthermore, the Grand Canyon should evaluate data from the past 10 years since the publishing of the Climate Action Plan (National Park Service 2022).

In order to improve its preparedness for the impacts of climate change, this paper recommends improving the Grand Canyon's Climate Action Plan with more specific adaptation options for dealing with drought, reduced stream flows, reduced water quality, and ecosystem mortality events.

Adapting to Drought & Reduced Stream Flows

Five distinct biotic communities exist in the Grand Canyon's ecosystem including the Mixed Conifer Forest, Ponderosa Pine Forest, Pinyon-Juniper Woodland, Desert Shrub, and Riparian. Introducing more drought-resistant plants early on could help improve the resilience of these communities. Another option that should be researched further is conditioning native plants to increase drought tolerance through early exposure to drought. Not enough research exists to determine if this strategy is relevant to Grand Canyon National Park, especially since this strategy may be species specific (Valliere 2019).

The Grand Canyon National Park needs to increase its water efficiency and reduce water usage across its facilities to adapt to drought and stream flows. Installing low-flow appliances at administrative sites can increase water efficiency (Halofsky et al. 2018). Other National Parks, such as Golden Gate National Recreation Area have undertaken several methods to conserve water. These methods include using low-flow faucets, dual-flush toilets, using a rainwater catchment system to irrigate landscaped areas and supply water to flush toilets (National Park Service 2021).

To prevent drought in the Colorado River Basin, the Grand Canyon National Park should adopt strategies addressing the river's various landscapes (e.g. wetlands, surrounding uplands and buffers, areas contributing to groundwater recharge). For example, installing buffers within 100 meters of the river would reduce the rate of water flow to and from the wetland, enhancing its water holding capacity. Also, withdrawing less water from the river's confined aquifers would increase groundwater storage and recharge. These strategies can collectively lower the chance of drought in the basin (Staffen et al. 2019).

Another approach that the Grand Canyon National Park could consider is restoring the river's hydrologic functions disturbed by droughts. This could be achieved by implementing a land use management scheme that oversees the river's runoff, infiltration rates, and base flow. For example, using ditch plugs or adjusting compacted soils can help improve water's residence time in areas impaired by drought events. Moreover, removing legacy sediment can help restore hydrologic cycles in floodplains and wetlands (Staffen et al. 2019). Furthermore, increased nitrogen exports and nutrient loading induced by droughts can be alleviated by creating sediment basins to trap nutrients before they flow into the river or its streams or restoring perennial vegetation near the river (Staffen et al. 2019).

Adapting to Wildfires and Heatwaves

One crucial aspect of the NPS' climate change response is a comprehensive wildfire response system. Adaptive management strategies for wildfires and heatwaves are key to reducing their impacts on water quality. Wildfires can be better managed in Grand Canyon National Park through strategies such as reducing hazardous fuels, reducing other disturbances that contribute to erosion (such as off-road vehicles, unregulated livestock, etc.), and using better road management practices to reduce erosion (Halofsky et al. 2019).

Fuel reduction treatments in forests can include a combination of 1) forest thinning and 2) prescribed burning. Forest thinning is an important forest management tool that consists of removing some trees to give others room to grow. Trees stressed by overcrowding in forests may reach a point where they can longer be supported by the site and growth rates in the forest can decline. Thinning allows trees to have more resources and improve forest health. This enables forests to better withstand fire. Thinning changes how wildfires behave and makes it less destructive when it burns through an area (Punches 2004). Prescribed fires can reduce hazardous fuels that have built up in the environment and thereby prevent a destructive wildfire. Parks must complete a fire management plan and prescribed burn plan for the prescribed fire to be permitted. Prescribed burning can also favor the regeneration of different species in the forest, improving the biodiversity of the forest and its resilience in the face of wildfires. By implementing these strategies to adapt to wildfires, Grand Canyon National Park can improve water quality in the face of climate change (National Park Service 2022).

In Grand Canyon National Park, wildfires that are naturally occurring and low-intensity could help clear the forest and add important nutrients to the soil, especially for Ponderosa Pines on the North Rim and South Rim of Grand Canyon National Park. Today, fire managers can use natural and prescribed fires, hazard fuel reduction, and fire effects monitoring to help restore the Ponderosa Pine Forest in Grand Canyon National Park (National Park Service 2018).

Adaptive management of heatwaves should deal with both 1) heatwave's impacts on human health and 2) heatwave's impacts on Grand Canyon ecosystems. Heatwave's impacts on Grand Canyon ecosystems is addressed in the ecosystem mortality events section. By implementing a heat wave action plan, Grand Canyon National Park can improve awareness about the health impacts of heat waves and protect the health of visitors and park rangers. Effective heat waves action plans include both prevention strategies and direct responses in the case of a heat wave. Prevention should include information dissemination about the health-impacts of heat waves, especially for young children and the elderly. Direct response should consist of strong search-and-rescue capacity from May to September. The park should also consider shutting down outdoor programs or even closing down the park when temperatures exceed 105°F.

Adapting to Ecosystem Mortality Events

Ecosystem protection is another realm at the forefront of the NPS' fight against climate change, and fostering an ecosystem that is resilient to the myriad effects of climate change will be a defining struggle for the NPS in the coming decades. Having a strong understanding of the interaction between flora and fauna in the ecosystem is crucial, and this certainly applies to GCNP. First and foremost, this knowledge should be used to determine optimal population sizes for large organisms, so that they can be kept in check and will not be overpopulated and run the vegetation populations into the ground, but also will not be underpopulated (National Park Service 2018).

Ensuring that visitors to the Grand Canyon stay on trails can help improve the resiliency of dominant forest species such as the Pinyon Juniper Woodland. Extremely sensitive biological soil crust and other vegetation can be damaged by visitors walking off of the established trails. Creating public awareness about the importance of staying on trails can improve the resiliency of biota like the Pinyon-Juniper Woodland (National Park Service 2018).

Restoring vegetation can be aided through maintaining and restoring wetland structure by 1) controlling woody species invasion; 2) when controlling invading brush with heavy equipment such as a forestry mower, only work on frozen surfaces or dry substrate conditions (Staffen 2019). Also, equipment such as tracks that exert low pressure to the ground can lessen damage to soil and vegetation and are suitable to varying ground conditions.

As touched on earlier, another key metric for the NPS and GCNP to keep an eye on is prescribed fire frequency and magnitude. Conducting studies and simulations to determine the optimal amount of prescribed fire is important to minimize the risk of catastrophic wildfire and its effects on ecosystem services and the organisms that live within (National Park Service 2018).

Ensuring adequate surface water sources is key to protecting high-priority wildlife and easing pressure on riparian (riverbank) vegetation. That means water-retaining structures around springs must be a priority, especially as it pertains to habitat and freshwater sources for wildlife. In the GCNP, the Colorado River is the lifeblood of the ecosystem, so naturally, ensuring an adequate streamflow is a paramount priority.

One study that was conducted by the Phoenix, AZ branch of the US Bureau of Reclamation on the spatial distribution of four native fish species that live in the Little Colorado River (LCR) in GCNP, and how water and habitat conditions affect those distributions. The authors found that there were distinct differences in habitat conditions upstream and downstream of Chute Falls in this section of the LCR, which had a significant impact on which fish species could survive (Robinson, Kubly, Clarkson, Creef 1996).

With that in mind, one solution is introducing these species into other areas of the LCR could benefit the fish populations in the long term. A key management option to consider for the NPS is undertaking a physical alteration of Chute Falls to decrease the steep vertical drop, which would allow the fish to move upstream on their own without needing the NPS to manually relocate fish (Robinson, Kubly, Clarkson, Creef 1996).

A report published by Colorado State University zeroed in on several additional management strategies for promoting the resilience and adaptability of desired (or native) fish species. First, identifying and restoring the “warm-adapted” populations” of the desirable fish species that belong in the GCNP. Second, to place limits on the pressure that anglers can put on desirable fish species, especially for the stream sections that are approaching or have reached temperature thresholds. Thirdly, fortifying the population sizes of the desired fish species, and reducing the populations of undesirable fish through removal (using techniques such as electrofishing, chemical removal, or genetic swamping, or encouraging increased harvesting) (Fink et al. 2019). In addition, increasing public awareness, through education, of relevant diseases, and conducting campaigns to treat or remove fish infected with those diseases. However, this must be balanced with a concerted effort to maintain diverse communities with different species. Conservation efforts must not lead to conserving one species at the expense of all the others. Furthermore, minimizing the concentrations of pollutants and contaminants in the water is crucial, especially in regards to preserving a wide range of habitat diversity – in other words, pollution must be kept to a minimum to ensure that all fish habitats can still support the fish that live there (Fink et al. 2019).

That study touched on a central concern in conservation efforts: habitat fragmentation. In response to high potential extirpation, national parks like GCNP can act to increase species' area of viable habitat, especially by ensuring habitat connectivity and minimizing fragmentation for organisms such as birds (National Park Service). Fragmentation can be amended by removing instream barriers, as well as preemptively replacing or retrofitting culverts to ensure they will not contribute to future fragmentation later on in the event of low base flows as a result of drought and climate change (Fink et al. 2019).

The National Parks Conservation Association (NPCA) is an organization that focuses on legislation that will protect national parks, including air and water quality and climate resiliency. Some of the gains made include the application to national parks of the Environmental Protection Agency's (EPA) Regional Haze Rule – responsible for an annual reduction of 52 million tons of CO_2 emissions – and the Bureau of Land Management's (BLM) Methane Rule. Now, the NPCA is turning its attention to wildlife habitat protection, a key component of which is avoiding habitat fragmentation (National Parks Conservation Organization 2017).

Researchers at Northern Arizona University concluded that future Colorado River cutthroat trout (CRCT) conservation efforts should focus on preventing further loss of habitat from CRCT segments, and expanding segment length for these isolated populations where possible, which can be aided by tools such as regional stream temperature models (Northern

Arizona University 2017). In practice, a sizable chunk of this task falls on preventing oil and gas development in national parks. To that end, the NPCA has backed a Master Leasing Plan, which aims to protect both the Arches and Canyonlands National Parks from oil and gas projects (National Parks Conservation Organization 2016). We propose a similar course of action for the GCNP.

Beyond just the scope of the NPS and its ability to regulate the activities within the boundaries of the GCNP, the need for cooperation and collaboration among the seven US states and two Mexican states in conserving the Colorado River has never been as pressing. It is essential that each of these state governments – as well as the American and Mexican federal governments – agree on a framework of environmental protection to ensure the preservation of the Colorado River. There must also be a seat at the table for other stakeholders, especially making sure that indigenous communities' water rights must be honored. Furthermore, ensuring adequate environmental flows – despite reduced water allocations for other stakeholders – must be factored into Colorado River management plans. (Fleck, John, and Castle. 2022).

In addition, from the US federal government perspective, there are some actions that the Secretary of the Interior – as the oversight for departments like the National Park Service – can undertake unilaterally. These include appropriately factoring into water allocations the evaporation in the Lower Basin reservoir, as well as increasing storage credits for Lake Mead. Also, the Secretary can take the lead on creating a Colorado River advisory committee, which can and should include all stakeholders previously mentioned: both American and Mexican states, and indigenous tribes. Adding in the help of the state governments, the Secretary can enact more policies to protect the river. These include limits on new development in the Upper Basin, leading water reduction negotiations, supplementing the water supply for the river with water recycling or desalination projects, and more.

Categories for Table: Community-based Actions/Planning, Biota, Water Usage and Efficiency

Adaptation Strategy	**Climate Impact Addressed**
Prescribed burning	**Drought & Streamflow Impairment**

Adaptation Strategy	Climate Impact Addressed
	Ecosystem Mortality
Conditioning native plants to increase drought tolerance	Water Quality Ecosystem Mortality Drought & Streamflow Impairment
Installing low-flow appliances (low flow faucets, dual-flush toilets, etc.	Water Quality Drought & Streamflow Impairment
Using a rainwater catchment system for irrigation and water supply	Water Quality Drought & Streamflow Impairment
Installing buffers to enhance water holding capacity	Drought & Streamflow Impairment
Withdrawing less water from confined aquifers	Drought & Streamflow Impairment
Land use management scheme overseeing river's runoff, infiltration rates, and base flow	Ecosystem Mortality Water Quality Drought & Streamflow Impairment
Removing legacy sediment	Drought & Streamflow Impairment
Creating sediment basins	Water Quality Drought & Streamflow Impairment
Forest thinning (fuel reduction treatment)	Drought & Streamflow Impairment Ecosystem Mortality
Fire effects monitoring	Drought & Streamflow Impairment Ecosystem Mortality

Adaptation Strategy	Climate Impact Addressed
Create heatwave action plan	Drought & Streamflow Impairment Ecosystem Mortality
Determine optimal population sizes for large organisms	Ecosystem Mortality
Ensure that visitors to the Grand Canyon stay on trails	Ecosystem Mortality
Conduct studies and simulations to determine the optimal amount of prescribed fire	Drought & Streamflow Impairment Ecosystem Mortality
Ensure adequate surface water sources, including water-retaining structures around springs	Water Quality Drought & Streamflow Impairment Ecosystem Mortality
Introduce four native fish species residing in the Little Colorado River into its other areas	Ecosystem Mortality
Decrease the steep vertical drop of Chute Falls	Drought & Streamflow Impairment Ecosystem Mortality
Ensuring habitat connectivity and minimizing fragmentation for organisms such as birds	Ecosystem Mortality
Use regional stream temperature models	Ecosystem Mortality
A framework of environmental protection for the preservation of the Colorado River	Water Quality Ecosystem Mortality
Appropriately factoring into water allocations the evaporation in the Lower Basin reservoir	Ecosystem Mortality

Adaptation Strategy	Climate Impact Addressed
Increasing storage credits for Lake Mead	Ecosystem Mortality
Creating a Colorado River advisory committee	Ecosystem Mortality
Limiting new development in the Upper Basin	Water Quality Ecosystem Mortality
Leading water reduction negotiations	Ecosystem Mortality
Supplementing the water supply for the river with water recycling or desalination projects	Water Quality Ecosystem Mortality

Conclusion

This paper presents an overview of major climate-related extremes that are likely to impact the Colorado River in Grand Canyon National Park and adaptation options for ecosystems and communities in the park. While the climate-related impacts discussed are not exhaustive, they are areas of high priority for the park and for the Colorado River. Drought and streamflow, water quality, and ecosystem mortality events are likely to have extensive impacts that should be addressed. Already, the Colorado River's annual stream flows have fallen 19% compared to the 20th century average and climate change is anticipated to further deplete the river over time as drought increases in intensity and frequency in the region. Furthermore, the water quality of the Colorado River in the Grand Canyon is threatened by wildfires and heat waves which will increase in occurrence due to rising temperatures. By destroying forests and aggravating soil erosion, wildfires can negatively impact water quality of the river. Heatwaves can also contribute to a decrease in water quality and threaten the health of visitors of the park. Ecosystem mortality events are also expected to increase. There have already been observed impacts on species native to the Colorado River, like the humpback chub and the Colorado River cutthroat trout.

The gaps in the National Park Service's plans reveal a lack of preparedness for these changes and suggest the park should create an updated climate adaptation plan incorporating scenario-based planning and detailing specific adaptation strategies. The range of adaptation strategies we suggest are the beginnings of potentially expansive documentation and data collected by the Grand Canyon Park Service across the region. Planning for these various impacts is especially pressing given that some of these impacts have already been observed and are expected to intensify. Ultimately, it is crucial that the National Park Service in the Grand Canyon considers how climate change will impact the Colorado River and surrounding ecosystems and communities.

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