National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Natural Resource Conditions at Glen Canyon National Recreation Area

Findings & Management Considerations for Selected Resources

Natural Resource Report NPS/SCPN/NRR—2022/2374

AUTHENTICATED
U.S. GOVERNMENT
INFORMATION
GPO

ON THIS PAGE
John Spence, Deputy Chief of Natural Resources & Chief Scientist at Glen Canyon National Recreation Area and Rainbow Bridge National Monument, retired in January 2021, after almost 30 years of NPS service. He actively engaged in management and research throughout his esteemed career, contributing foundational knowledge of Colorado Plateau flora and spring-based ecosystems. His legacy will speak for itself as his contributions to science continue to inform the effective management of Colorado Plateau resources well into the future.
Image Credit: NPS.

ON THE COVER
Top: Cottonwood gallery forest along the Escalante River. Middle: Escalante River during September 2010 flood (left). Waterpockets (center). Northern leopard frog (right). Bottom: Spring habitat (left). Cardinal flower (top right). Un-grazed vegetation at East End spring
Image Credits: ©Douglas Wilhelm Harder (Northern leopard frog), remaining photos are NPS.

Natural Resource Conditions at Glen Canyon National Recreation Area

Findings & Management Considerations for Selected Resources

Natural Resource Report NPS/SCPN/NRR—2022/2374

Jeff Albright[1], Kim Struthers[2], Lisa Baril[2], John Spence[3], Mark Brunson[2], Ken Hyde[3]

[1] National Park Service
Fort Collins, Colorado

[2] Utah State University
Logan, Utah

[3] National Park Service
Page, Arizona

April 2022

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible and technically accurate.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available in digital format from the Natural Resource Condition Assessment Program and the Natural Resource Publications Management website. If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov.

Please cite this publication as:

Albright, J., K. Struthers, L. Baril, J. Spence, M. Brunson, and K. Hyde. 2022. Natural resource conditions at Glen Canyon National Recreation Area: Findings & management considerations for selected resources. Natural Resource Report NPS/SCPN/NRR—2022/2374. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/nrr-2293112.

NPS 608/180297, April 2022

Contents

Page

Figures....vii

Tables....ix

Appendices....xi

Executive Summary....xiii

Acknowledgments....xxi

List of Acronyms....xxiii

Glossary....xxv

Natural Resource Condition Assessments – Introduction....xxvii

Conceptual Framework for Assessing Resource Conditions and Influences....xxvii

NRCA Technical Report....xxviii

Focal Resources and Drivers & Stressors Summary for GLCA's NRCA....xxviii

Chapter 1. Introduction to Park Setting and Resources....1

1.1. Location....1

1.2. Setting and Resources....3

1.2.1. Colorado River....3

1.2.2. Complex Desert and Water Environments....4

1.2.3. Flora & Fauna....6

Chapter 2. Drivers and Stressors....9

2.1. Human History....9

2.2. Visitor Use & Recreation....10

2.3. Non-native Invasive Plants and Vegetation Transitions....11

2.4. Ranching & Livestock Management (Grazing)....14

2.5. Air Quality (Pollution)....15

2.6. Resource Extraction....18

2.7. Climate Change....19

2.8. Upland Watershed Activities....25

Contents (continued)

Page

Chapter 3. Focal Resource Evaluations 27

3.1. Tinajas (Gap Analysis) 30

3.1.1. Background & Importance 30

3.1.2. Status of Knowledge 31

3.1.3. Discussion 38

3.2. Water Quality of Springs & Seeps (Gap Analysis) 41

3.2.1. Background & Importance 41

3.2.2. Status of Knowledge 41

3.2.3. Discussion 47

3.3. Springs & Seeps (Condition Assessment) 51

3.3.1. Background & Importance 51

3.3.2. Study Framework 52

3.3.3. Data & Methods 53

3.3.4. Results & Discussion 54

3.4. Riparian Zone (Condition Assessment) 64

3.4.1. Background & Importance 64

3.4.2. Study Framework 65

3.4.3. Data & Methods 65

3.4.4. Results & Discussion 69

3.5. Amphibians (Gap Analysis) 78

3.5.1. Background & Importance 78

3.5.2. Status of Knowledge 78

3.5.3. Discussion 82

3.6. Northern Leopard Frog (Condition Assessment) 85

3.6.1. Background & Importance 85

3.6.2. Study Framework 85

Contents (continued)

Page

3.6.3. Data & Methods 86

3.6.4. Results & Discussion 87

3.7. Fishes (Condition Assessment & Gap Analysis) 95

3.7.1. Background & Importance 95

3.7.2. Study Framework 95

3.7.3. Data & Methods 98

3.7.4. Results & Discussion 101

Chapter 4. Management Considerations 115

4.1. Manager-Scientist Review 116

4.2. Review Outcomes Summary 117

4.3. Review Outcomes by Focal Resource 119

4.3.1. Tinajas Summary 119

4.3.2. Springs & Seeps, including Water Quality, Summary 121

4.3.3. Riparian Zone Summary 122

4.3.4. Amphibians, including Northern Leopard Frog, Summary 123

4.3.5. Fishes Summary 123

4.4. Conclusion 124

Literature Cited 125

Figures

Page

Figure I-1. The DPSSR conceptual framework is used to report drivers, stressors, states, and responses in NRCA projects (adapted from Harwell et al. (2019) and the Office of National Marine Sanctuaries (2020)). xxviii

Figure 1.1-1. NPS map of GLCA and surrounding region. Figure Credit: NPS/Harpers Ferry Center. 2

Figure 2.7-1. Historical (1915–2015) and predicted (2020–2100) departure from baseline (1970–2010) median temperature under RCP 4.5 and RCP 8.5. 21

Figure 2.7-2. Historical (1915–2015) and predicted (2020–2100) percent departure from baseline (1970–2010) median precipitation under RCP 4.5 and RCP 8.5. 22

Figure 3-1. Two levels of evaluations are reported in NRCA studies depending on data availability: condition assessment and gap analysis. 27

Figure 3-2. Indicators of condition rating classes and colors. 27

Figure 3-3. Proportion of GLCA's area in eight watersheds. 28

Figure 3-4. GLCA's selected focal resources were evaluated and reported within eight watersheds. 29

Figure 3.1.2-1. Potential area for supporting tinajas. 32

Figure 3.1.2-2. Tinajas mapped in Waterpocket Fold area of analysis. 33

Figure 3.2.2-1. Locations of springs with water quality data. 42

Figure 3.2.2-2. Mean spring discharge by month. 44

Figure 3.2.2-3. Percent of springs sampled in each discharge class. 44

Figure 3.2.2-4. Mean invertebrate richness across taxonomic orders at springs (inset shows mean and total richness by genera and order). 47

Figure 3.3.4-1. Distribution of confirmed and potential springs in GLCA. 56

Figure 3.3.4-2. Mean plant species richness by watershed. 57

Figure 3.3.4-3. Mean plant species richness by spring type. 57

Figure 3.3.4-4. Distribution of 29 springs by functional category. 58

Figure 3.4.4-1. Mean and peak annual discharge for the Escalante River (gage ID: 09337500) and Dirty Devil River (gage ID: 09333500) stream gages. 69

Figures (continued)

Page

Figure 3.4.4-2. Boxplots showing the mean, median, lower quartile, upper quartile, and outliers for historical and contemporary total annual and monthly (April–October) flow data for the Escalante River and Dirty Devil River USGS stream gages. 70

Figure 3.4.4-3. Estimated monthly streamflow for ungauged streams (Halls Creek, Wilson Creek, Coyote Gulch, Lake Canyon) and actual monthly streamflow for the Escalante River (gage ID: 09337500) and Dirty Devil River (gage ID: 09333500). 71

Figure 3.4.4-4. Aquatic intactness for HUC6 subwatersheds. 73

Figure 3.4.4-5. Percent of total stream length in each departure class for Dirty Devil, Escalante, Coyote Gulch, and Harris Wash. 74

Figure 3.5.2-1. Locations of amphibians detected throughout GLCA. 81

Figure 3.6.4-1. Extant, extirpated, and unknown status site locations for northern leopard frog populations. 89

Figure 3.6.4-2. Percent cover of wetland vegetation during 1995 and 2017 at 11 northern leopard frog locations. 92

Figure 3.7.2-1. Locations of study areas for fishes. 97

Figure 3.7.4-1. Percent departure in total annual flow from estimated natural flows for the Paria River (1924–2018) and San Juan River (1929 to 2018) USGS stream gages. 101

Figure 3.7.4-2. Boxplots of the mean, median, lower and upper quartiles, and outliers for estimated and observed total annual flow and monthly (April–October) flow for the Paria and San Juan rivers. 102

Figure 3.7.4-3. Boxplots showing the mean, median, lower quartile, upper quartile, and outliers for historical and contemporary total annual and monthly (April–October) flow data for the Escalante River and Dirty Devil River USGS stream gages. 103

Figure 4.2-1. The proportion of manager responses by focal resource and action category that were discussed during GLCA's manager-scientist meeting. 118

Figure 4.2-2. The proportion of manager responses by focal resource and driver or stressor that were discussed during GLCA's manager-scientist meeting. 118

Figure C-1. The drivers and stressors conceptual model used to depict and discuss influences of resource conditions. 162

Tables

Page

Table ES-1. Summary of GLCA's natural resource condition assessment indicators of condition ratings. xv

Table I-1. The primary drivers-pressures and stressors influencing the conditions (states) of GLCA's focal resources. xxix

Table 2.3-1. Non-native plant species that are in GLCA and listed on Arizona and/or Utah state noxious weed lists. 12

Table 3-1. HUC8 watershed summary for GLCA. 28

Table 3.1.3-1. Proposed study details for tinajas. 39

Table 3.2.2-1. Core water quality data for springs & seeps by accessibility to grazing. 45

Table 3.2.3-1. Proposed study details for water quality of springs & seeps. 48

Table 3.3.2-1. Study details for the springs & seeps condition assessment. 53

Table 3.3.3-1. Functional categories for springs & seeps impacts. 54

Table 3.3.4-1. Springs & seeps condition ratings summary. 59

Table 3.4.2-1. Study details for the riparian zone condition assessment. 65

Table 3.4.4-1. List of water quality impairments for perennial streams in GLCA excluding the Colorado River and Lake Powell. 74

Table 3.4.4-2. Riparian zone condition ratings summary. 75

Table 3.5.2-1. NPSpecies (2020) list of amphibians and observations of occurrence. 79

Table 3.5.3-1. Proposed study details for amphibians. 82

Table 3.6.2-1. Study details for the northern leopard frog condition assessment. 86

Table 3.6.4-1. Summary of extant, extirpated, and unknown status for northern leopard frogs by location. 90

Table 3.6.4-2. Northern leopard frog condition ratings* summary. 93

Table 3.7.2-1. Study details for the fishes condition assessment. 96

Table 3.7.4-1. List of water quality impairments for the evaluated streams. 104

Table 3.7.4-2. Fishes condition ratings* summary. 113

Table 4.1-1. Action categories used to facilitate manager-scientist discussion of responses. 117

Tables (continued)

Page

Table A-1. GLCA natural resource manager question, need, abbreviated answer, and NRCA report chapter/section for further information summary. 151

Table B-1. Condition rating statements for the status of springs & seeps indicators. 157

Table B-2. Condition rating statements for the status of riparian zone indicators. 157

Table B-3. Condition rating statements for the status of northern leopard frog indicators. 158

Table B-4. Condition rating statements for the status of fishes indicators. 159

Table B-4. Condition rating statements for the status of fishes indicators. 160

Table C-1. The drivers and stressors conceptual model shown in Figure C-1, depicted in tabular format. 163

Table D-1. Responses for tinajas. 165

Table D-2. Responses for water quality of springs & seeps. 166

Table D-3. Responses for springs & seeps. 167

Table D-4. Responses for riparian zone. 168

Table D-5. Responses for amphibians. 169

Table D-6. Responses for northern leopard frog. 170

Table D-7. Responses for fishes. 171

Appendices

Page

Appendix A. GLCA Manager Questions and Information Needs 151

Appendix B. Condition Rating Statements 157

Appendix C. Drivers and Stressors Diagram & Tabular View 161

Appendix D. Manager-Scientist Responses by Resource and Driver or Stressor 165

Executive Summary

Glen Canyon National Recreation Area (GLCA) encompasses more than 0.5 million ha (1.25 million ac) and extends over 322 km (200 mi) from its northern boundary in southern Utah to its southern boundary in northern Arizona. It is one of the most rugged, remote, and floristically diverse national parks on the Southern Colorado Plateau (Thomas et. al 2005) and has more than 4,900 km (3,045 mi) of waterways flowing through its eight Hydrologic Unit Code (HUC 8) watersheds. GLCA's larger perennial rivers include the Colorado, Escalante, Dirty Devil, San Juan, and Paria, with smaller perennial and intermittent streams flowing into each of these rivers. After the creation of the Glen Canyon Dam, Lake Powell formed, covering 13% of the park's total land area when full and the national recreation area attracts over 4 million visitors annually, and in 2019 GLCA ranked 19th highest in recreational visits out of all national parks.

The National Park Service Natural Resource Condition Assessment Program selected GLCA to pilot its new NRCA project series. NRCA projects evaluate the best available science to provide park managers with reliable, actionable information pertaining to natural resource conditions in their park. For the park-selected focal study resources, this includes consideration of drivers and stressors known or suspected of influencing resource conditions; assessment of current conditions and trends for indicators of condition; and potential near-term and future activities or actions managers can consider, improving their knowledge and management of natural resources in parks. For focal resources that lack adequate data to assess current conditions, a gap analysis is provided (in lieu of a condition assessment) to highlight the present status of knowledge of the resource and to suggest useful indicators, data, and studies for further consideration and investigation. Park managers are encouraged to identify information needs and pose questions during the NRCA scoping process, with the understanding that information will be provided to help address those needs and answer those questions when possible. For a comprehensive list of GLCA managers' questions and needs, please refer to Appendix A, Table A-1.

The focus of GLCA's NRCA study was the water-dependent resources—tinajas, springs & seeps, including water quality, riparian zone, amphibians, including the northern leopard frog (*Lithobates pipiens*), and small, native fishes—that are found off the mainstem Colorado River. Managers were interested in these particular environments and the natural resources that depend on them because they are less studied, and the habitats are "biodiversity hotspots" due to the intersection of complex desert and freshwater ecosystems in a region limited by water. The following summaries highlight the key findings of GLCA's focal resource drivers and stressors (Chapter 2), states (Chapter 3), and manager responses (Chapter 4).

Tinajas

Tinajas (Spanish word for clay jar and also known as waterpockets, ephemeral pools, and potholes) represent the most numerous and widespread sources of surface water in GLCA, and the weathering pits (shallow depressions in rock) at Cookie Jar Butte may be some of the deepest ones in the world (Nethoff et al. 1995). Both serve as significant oases for wildlife and plants and fill with precipitation or snowmelt on wind- or water-eroded sandstone surfaces. GLCA managers were interested in

knowing where tinajas are most likely to occur in the park, and based on a limited mapping exercise, an area of 806 km^2 (311 mi^2) was identified. A more focused analysis in the Waterpocket Fold area of GLCA revealed a conservative estimate of 588 individual tinajas and 47 tinaja clusters but further evaluation is needed for a more comprehensive understanding of where this resource is located.

Because tinajas are a water-based resource, changing temperatures and precipitation patterns affect the amount of water that is in them, which in turn affects the types of species that depend on them. Park managers were specifically interested in the types of endemic species that are likely to survive in these environments with increasingly drier and warmer climate. Unfortunately, the current status of knowledge for tinaja flora and fauna within GLCA is limited, thus the focal resource was evaluated as a gap analysis. While the limited inventories for three tinajas in the park did not report any biogeographically restricted or Colorado Plateau endemic species, the resource lends itself to a future focused condition evaluation and monitoring program. The plants in the three tinajas were found to be floristically distinct from the flora in tinajas farther north in Capitol Reef National Park (CARE) and in the park's riparian zone vegetation plots (Spence 1996a; Spence and Henderson 1993).

The potential for identifying additional locations and prioritizing the larger tinajas throughout GLCA, which hold more water for longer periods and are more likely to support vegetation, are especially important during the seasonal dry periods and longer drought cycles that the Colorado Plateau region is experiencing. While no other parks are managing this resource (only monitoring), potential management actions may include further location analysis given the vastness of tinajas throughout the park and prioritizing those locations for actions such as installing fence to exclude ungulates, managing backcountry use, and controlling invasive species. With those management options in mind, four potential indicators of condition for monitoring—water quantity, water quality, community composition, and disturbance—are suggested for future study and management, especially to determine whether tinajas serve as oases for endemics. Partnering with CARE, which connects to GLCA along the Waterpocket Fold—an extensive, upthrusted sandstone geologic feature that extends 160 km (100 mi)—and other national parks to prioritize areas for management will create a landscape-level management framework, reflecting this resource's importance throughout the Colorado Plateau region. Such a partnership may be the first of its kind since many parks only monitor tinajas.

Springs & Seeps (including water quality)

Springs & seeps are biodiversity hotspots, serving as reliable freshwater sources for wildlife and plants, especially endemic and relict species, in an arid environment such as GLCA. Understanding the water quality of springs & seeps is necessary for managers to make decisions about the appropriate actions to take to ensure the health of these water-based environments.

While springs & seeps were evaluated as a condition assessment using two indicators of condition (Table ES-1), the water quality of springs & seeps has been monitored only intermittently since 1965, and not all data of interest have been systematically collected; therefore, water quality was evaluated separately as a gap analysis. We combine the findings for both focal resource topics in the following summary.

Table ES-1. Summary of GLCA's natural resource condition assessment indicators of condition ratings.

Focal Resource	Indicator	Condition Rating	Trend
Springs & Seeps	Native Plant Distribution and Occurrence	Good	Unknown
	Impacts	Fair	Unknown
Riparian Zone	Water Quantity and Availability	Fair	Deteriorating
	Stream/Watershed Health	Fair	Unknown
	Vegetation	Poor	Unknown
Northern Leopard Frog	Occupancy	Poor	Deteriorating
	Reproduction	Good	Stable
	Disease	Good	Stable
	Plant Encroachment	Poor	Deteriorating
Fishes	Water Quantity and Availability (San Juan, Escalante, Dirty Devil, Paria rivers)	Fair	Deteriorating
	Water Quality (San Juan, Escalante, Dirty Devil, Paria rivers)	Good/Fair	Unknown
	Biological Community (Lower Escalante and San Juan rivers)	Poor	Stable
	Biological Community (Upper Escalante River)	Good	Stable
	Habitat Quality and Availability (Escalante and San Juan rivers)	Unknown	Unknown

Available spring & seep locations for GLCA were compiled into one database, confirming 250 locations, mostly in the Navajo Sandstone and Kayenta Formation. An additional 348 springs were unconfirmed. Surveys at 185 springs documented 144 native species, representing 93% of GLCA's and 66% of Colorado Plateau's recorded wetland species. While there was variation in wetland, relict, and endemic species across watersheds and spring types, they all exhibited similar richness. In summary, the findings suggest native wetland species are dominant in GLCA's surveyed springs & seeps, with a low occurrence of non-native invasive plants, resulting in a good condition rating for the native plant distribution and occurrence indicator of condition. However, due to large differences in survey sample sizes, the trend is unknown.

Using a combined score for eight categories of spring impacts, 65% of 29 surveyed springs were intact but approaching functioning at-risk (a degraded condition from good). The primary impacts included livestock use and impacts associated with developments for livestock watering, effects of drought, and some presence of non-native plants. Livestock grazing is a primary stressor of springs & seeps and has occurred in the region for more than 100 years. It is also approved in the park's enabling legislation and is widespread throughout GLCA, with observed impacts to springs & seeps. Further analysis of resource conditions and locations of grazing allotments will help GLCA managers determine whether adjustments should be made to the timing and locations of grazing practices. Overall, these combined impacts at surveyed springs resulted in a condition rating of fair, with an unknown trend due to single site visits.

In summarizing the water quality data for springs & seeps, the highest mean discharge was recorded in May. The discharge magnitude for most springs & seeps was in the 10–100 mL/s and 100–1,000 mL/s classes, although 9% of the measurements were below the instrument's ability to record, which is not uncommon in Southern Colorado Plateau springs. No significant differences occurred in pH, dissolved oxygen, or temperature between springs that were accessible versus inaccessible to grazers. Specific conductance (an indicator of dissolved solids) was higher in springs accessible to grazers; however, some springs have naturally higher specific conductance, so it is unclear whether this is a result of grazing disturbance and requires further study. No contaminants were present (at the time of data collection) and aquatic invertebrate order richness averaged 6.0 across sampled springs.

While a condition rating for the water quality of springs & seeps was not assigned, a revised spring monitoring protocol will be implemented at the park, which may include the following potential indicators of water quality condition—water quantity, core parameters (temperature, pH, dissolved oxygen, specific conductance), toxic parameters (uranium, nitrite, nitrate, trace metals), and benthic invertebrates—and provide the necessary data for future condition reporting.

A significant data gap is the understanding of groundwater residence times, which is of great importance to the health of springs & seeps since they are groundwater-dependent ecosystems. The biggest threat to shaded gardens and springs in alcoves is a decline in groundwater discharge due to changing precipitation—amount, duration, and timing—further highlighting the pressing need for groundwater studies. Potential evapotranspiration for exposed hillslope springs is likely a serious concern (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, pers. comm, 11 May 2021). In addition, documenting the array of native species, including endemics in these "biological hotspots," is critical prior to potential extirpation with rapidly changing temperatures and precipitation patterns.

Multidisciplinary and multi-partnership activities were identified as potential manager responses to address current conditions of springs & seeps and associated water quality. These activities include groundwater studies, continued monitoring activities, installing structures to capture water in pools to mitigate the effects of drought, rehabilitating spring openings to improve discharge and flow, assisting migration for certain endemics, installing fences to manage grazing access, and controlling species, especially non-native invasive plants that absorb large amounts of water. Additionally, backcountry users can be informed of the importance of these high priority resources and through interpretive and educational brochures and programs be enlisted to help maintain or improve water quality conditions.

Riparian Zone

Riparian zone areas along the Dirty Devil and Escalante rivers, Halls Creek, Lake Canyon, Coyote Gulch, Harris Wash, and Wilson Creek were evaluated as a condition assessment using three indicators of condition (Table ES-1). Riparian areas provide habitat for a multitude of wildlife, plant, and insect species in GLCA, supplement floodplain diversity and complexity, add channel stability, provide shading of streams by overhanging vegetation, which reduces stream temperature, and provide cover and habitat for fish.

For the stream/watershed health indicator, there were no impairments to water quality for the subset of streams analyzed, which included data for the most recent monitoring cycle (2018 and 2020) and the previous monitoring cycle (2014 and 2016). This indicator also included a measure of the aquatic intactness modeling results for HUC6 subwatersheds on the Colorado Plateau, which evaluated impacts from water demand, dams, diversions, developments, etc., resulting in a fair condition rating, with an unknown trend. This is due to the fact that 62.9% of the HUC6 watersheds that are partially or entirely within GLCA were rated as exhibiting moderately low or moderately high aquatic intactness.

For the water quantity and availability indicator of condition, stream gage data were limited to the Escalante and Dirty Devil rivers and the other locations were estimated. There were no significant declines in discharge for the Escalante (1943–2020) and Dirty Devil (1948–2020) rivers, although there was a moderate departure from historical/reference criteria for the Escalante River. Mean annual flow, annual variability in flow, and monthly flow variability were larger during the historical period than during the contemporary period for the Escalante River but not for the Dirty Devil River. For the remaining streams without gages, StreamStats predicted that the lowest 80% monthly exceedances occurred during September to January and that flows increased until July or August. Flows were then predicted to decline throughout the remainder of the year. For the water presence and persistence measure, most (89%) of the area in the riparian buffer did not exhibit any change from one wetted extent class to another between 1995 and 2017. Overall, the water quantity and availability indicator of condition was rated as fair, with a deteriorating trend.

The riparian zone vegetation indicator of condition revealed more degraded conditions as compared to the vegetation in springs & seeps. This is due in part to the minor to moderate conversion of the plant community from native to non-native, particularly along the Dirty Devil River. In addition, there has been invasion by at least some of the seven most problematic invasive species and there are large patches of invasive plants along most of the evaluated streams, warranting a condition rating of poor with an unknown trend.

Several drivers and stressors impact the proper functioning of riparian systems on the Colorado Plateau, but of all the factors, the amount and timing of precipitation is the most important (Scott et al. 2005). While managers are unable to influence precipitation timing and amount, they have been successful in partnering with other stakeholders to control non-native invasive plants, especially Russian olive (*Elaeagnus angustifolia*) within the Escalante Watershed. Establishing additional partnerships in other high priority watersheds to manage riparian zone impacts will contribute to resource resilience for all species that rely on this important habitat type.

Amphibians (including northern leopard frog)

The status of knowledge for amphibians as a group in GLCA is limited and was evaluated as a gap analysis, whereas the northern leopard frog has been more extensively studied throughout the park and was evaluated as a condition assessment, using four indicators of condition (Table ES-1). To date, six species of amphibian have been confirmed at GLCA, with the first checklist developed in the late 1940s and the first comprehensive survey occurring in 2003. Due to the park's large size and

limited surveys, more species are expected in addition to greater numbers, although detectability is problematic due to differences in the timing of breeding seasons between species.

The northern leopard frog has been monitored throughout the region since before the completion of the Glen Canyon Dam in 1966, although spatial and temporal data gaps exist for GLCA. After the creation of the dam, the elimination of frog habitat along the Colorado River effectively isolated populations in side canyons (Drost and Sogge 1995; O'Donnell and Mock 2008), and low genetic diversity and population inbreeding have been documented (O'Donnell and Mock 2008). A loss of 81% of all known northern leopard frog locations in GLCA has occurred since about the mid-1950s, representing a substantial decline in occupied areas over the last 70 years, warranting a poor condition rating with a deteriorating trend. However, evidence of northern leopard frog breeding at extant locations and the lack of a fungus-causing disease in swabbed individuals warranted good condition ratings with stable trends.

For the plant encroachment indicator of condition, there has been a significant increase in wetland plant cover at 11 locations (although not all occupied by the northern leopard frog), but especially in extant sites from 1995 to 2017, resulting in a poor condition rating with a deteriorating trend. At least some of this cover is *Phragmites australis* based on the information provided in the various sources cited, but because the plant encroachment analysis used a GIS-based analysis—maximum normalized difference vegetation index raster files—there were many instances in which the type of vegetation could not be distinguished (i.e., between native and non-native vegetation).

Primary amphibian stressors include impacts to habitat from grazing, non-native invasive plants, airborne and water contaminants, and the loss of water sources. Non-native predatory fishes and aquatic invertebrates are also a major threat to amphibians (Muths et al. 2006), but perhaps of greatest urgency is the need for follow-up surveys for all amphibians and for northern leopard frogs, especially at eight sites where the northern leopard frogs' current status is unknown but where they were observed during previous surveys. Potential manager responses identified to mitigate these stressors include prioritizing known locations of occupancy for management actions, especially in areas where off-road vehicle use may occur, erecting exclosures to mitigate livestock grazing impacts, and removing non-native invasive plants and animals to improve habitat conditions for all amphibians.

Fishes

Only eight of the 26 fish species in GLCA are native, and all eight are rare except for the speckled dace (*Rhinichthys osculus*). Four of the eight species are listed by the USFWS as federally endangered, and in an effort to protect three of the four remaining, non-game and non-threatened/endangered, species, a larger conservation effort among Wyoming, Arizona, Colorado, and Utah was initiated for the bluehead (*Catostomus discobolus*) and flannelmouth suckers (C. *latipinnis*), and roundtail chub (*Gila robusta*). For GLCA's combined condition assessment and gap analysis, four species were of interest, including the bluehead and flannelmouth suckers, roundtail chub, and speckled dace. These four species primarily occupy the San Juan, Escalante, Dirty Devil, and Paria rivers and their tributaries.

The condition ratings for the fish species of interest varied depending on the river or stream assessed and the data available for the 10 measures across the four indicators of condition listed in Table ES-1. Note that the biological community indicator is listed twice in Table ES-1 due to the different condition ratings assigned to the upper and lower Escalante River.

The water quality indicator of condition and the water quantity and availability indicator of condition were the only two that could be evaluated for all four rivers. Based on water quality data for core parameters (dissolved oxygen, sulfate, maximum temperature, pH, *E. coli*, total dissolved solids) and toxic parameters (hardness, aluminum, ammonia, fluoride, hydrogen sulfide, boron), no significant impacts to warm water aquatic life were reported, although mercury and emerging contaminants are not well studied and data for benthic macroinvertebrates are limited to the Escalante River from a 1998 survey. Combined, the water quality results (except for benthic macroinvertebrates, which is a data gap) for the San Juan, Escalante, Dirty Devil, and Paria rivers suggest a good/fair condition rating, with an unknown trend.

For the water quantity and availability indicator of condition, stream gage data for the Escalante and Dirty Devil rivers show that mean annual flow, annual variability in flow, and monthly flow variability were larger during the historical period than during the contemporary period. However, only historical vs. contemporary flows were significantly different for the Escalante River only. Observed annual flow volumes for the Paria River gage were not significantly different than estimated natural flow volumes. Variability in total annual and April–October flows for the Paria River were similar between estimated natural and observed flows.

For the San Juan River, observed annual flow volumes were 14% lower than estimated natural flow volumes through 1962, after which observed flow volumes substantially departed from natural conditions. The San Juan River gage, mean, median, and flow variability (particularly for high flows) both pre-dam and post-dam were lower than natural estimates, but there was no significant difference in the pre-dam flow vs. post-dam flows. However, there was a significant difference in estimated natural flow volumes vs. pre-dam flow volumes, which suggests that factors other than the dam are responsible for reduced flows in the San Juan River.

Overall, the results for the water quantity and availability indicator of condition suggest that flow volumes have been moderately degraded from natural or historical conditions, which indicates a fair condition for the four rivers assessed, with a deteriorating trend.

Information for the biological (fish) community and habitat quality and availability indicators of condition were available only for the Escalante and San Juan rivers. Additionally, condition ratings for the fish community indicator were reported separately for the upper and lower Escalante. For the upper Escalante River, all four species of interest were consistently present, and their populations were rated in good condition and appeared stable; in contrast, some of the species of interest in the lower Escalante and San Juan rivers were absent or severely reduced in numbers and dominated by non-native species, especially those that thrive in Lake Powell, reflecting poor conditions with stable trends based on frequency data.

For the habitat quality and availability indicator, data are lacking for the Escalante and San Juan rivers to evaluate the condition of the distribution and amount of bedform types and hydraulic features that reflect suitable habitat. Thus, the condition rating is unknown. This is a knowledge gap, in particular, long stretches of the Escalante and San Juan riverbeds have become exposed due to lower water levels with the extensive lowering of Lake Powell due to ongoing drought conditions.

The primary stressors for the four fish species of interest include non-native invasive plants encroaching on habitat, non-native invasive fish species, decreased water flow, and increasing temperatures and drought conditions. Developing multi-partnerships with the Utah and Arizona fish and game agencies and continued research were potential management responses identified for improving conditions for the fish species of interest and their habitats. This is especially the case given the long history of releasing non-native game fish in nearly all state waters and of water diversions for irrigation and cattle use that impede fish passage and alter water flows throughout the region's waterways.

Conclusion

Much uncertainty is related to many of the focal resource driver and stressor impacts, particularly climate change and its influence on GLCA's water-based resources, with increasing temperatures and drought frequency and duration. It's predicted that the overall temperature in GLCA will likely become hotter in the southern and lower elevations of the park as compared to the northern and higher elevations. And while there are no apparent trends in future projections of precipitation, droughts, including some of the driest and hottest periods on record since 2000, have become more common and are expected to worsen. While resources like springs & seeps may be more resilient to the effects of climate change compared to surface water-dependent systems, resource impacts are still expected. What remains unclear is the degree to which impacts will occur. Thus, a range of scalable management responses that are grounded in science were recommended in GLCA's NRCA report to help managers identify options based on what is achievable in the near-term and future to maintain, improve, or further inform natural resource conditions over time.

Acknowledgments

This report would not have been possible without funding and support from the NPS Natural Resource Condition Assessment Program, including Tammy Cook, Agreement Technical Representative, and the assistance from each individual listed below. We thank you for your contributions.

Study Plan Workshop Team: Jeff Albright (NPS NRSS-NRCA), Lisa Baril (USU), Mark Brunson (USU)**,** Tammy Cook (NPS NRSS-NRCA), Ken Hyde (NPS GLCA), Salek Shafiqullah (NPS DOI Regions 6–8), John Spence (NPS GLCA), Jen Strona (NPS Contractor/Partner), Kim Struthers (USU), Dave Vana-Miller (NPS DOI Regions 5–8)

Invited Study Plan Reviewers: Nicole Brandt Turner (NPS NRSS-BRD; amphibians, northern leopard frog**,** springs & seeps, water quality for springs & seeps), Jim Cheatham (NPS NRSS-ARD; air quality), Tim Connors (NPS NRSS-GRD; full study plan), Greg Eckert (NPS NRSS-BRD; springs & seeps, water quality for springs & seeps), Ken Hyde (NPS GLCA; full study plan), Lori Makarick (NPS NRSS-BRD; riparian zone), Mike Martin (NPS NRSS-WRD; riparian zone, springs & seeps, water quality for springs & seeps), Nic Medley (NPS NRSS-WRD; fish), Jordan Spaak (NPS NRSS-BRD; riparian zone, springs & seeps, water quality for springs & seeps), John Spence (NPS GLCA; full study plan), John Wullschleger (NPS NRSS-WRD; fish)

Invited Subject Matter Experts: John Bradford (USGS; contributed climate change content), Jodi Norris (NPS NRSS-IMD SCPN; authored Chapter 2 non-native invasive plants climate change text), Forrest Smith (NPS NRSS-GRD; authored Chapter 2 resource extraction oil and gas well text), Dean Tucker (NPS NRSS-WRD; provided water quality impairment data)

Invited Partner Reviewers: Ken Hyde (NPS GLCA; full report), John Spence (NPS GLCA; full report), Jennifer Strona (NPS Contractor/Partner; full report except fishes section), Patty Valentine-Darby (NPS Contractor/Partner; executive summary, amphibians, northern leopard frog, and fishes sections, and a general science communications review), Dana Witwicki (NPS NRSS-NRCA; full report except amphibians, northern leopard frog, and fishes sections)

Manager-Scientist Meeting Participants: Jeff Albright (NPS NRSS-NRCA), Lisa Baril (USU), Mark Brunson (USU)**,** Tammy Cook (NPS NRSS-NRCA), Ken Hyde (NPS GLCA), Salek Shafiqullah (NPS DOI Regions 6–8), John Spence (NPS GLCA), Kim Struthers (USU), Dana Witwicki (NPS NRSS-NRCA)

Policy & Publication Reviewers: Finally, we are also grateful to Alyssa McGinnity (NPS Contractor/Partner) and Michele Banowetz (NPS Contractor/Partner) for providing the final policy and publishing report review.

List of Acronyms

AML: Abandoned Mineral Lands

ARD: Air Resources Division

ARMI: Amphibian Research and Monitoring Initiative

AUM: Animal Unit Month

AWQD: Arizona Water Quality Division

AZGFD: Arizona Game and Fish Department

BLM: Bureau of Land Management

BRD: Biological Resources Division

CARE: Capitol Reef National Park

DOI: Department of Interior

DPSSR: Drivers, Pressures, Stressors, States, Responses

ERWP: Escalante River Watershed Partnership

EPMT: Exotic Plants Management Team

FCA: Focused Condition Assessment

GCWC: Grand Canyon Wildlands Council

GLCA: Glen Canyon National Recreation Area

GRD: Geologic Resources Division

HUC: Hydrologic Unit Code

IMD: Inventory & Monitoring Division

msl: Mean Sea Level

ORV: Off-road vehicle

NAIP: National Agriculture Imagery Program

NHD: National Hydrography Dataset

NM: National Monument

NP: National Park

NPS: National Park Service

NRA: National Recreation Area

NRCA: Natural Resource Condition Assessment

NRSS: Natural Resource Stewardship and Science Directorate (NPS Washington support office)

NWIS: National Water Information System

SCPN: Southern Colorado Plateau Inventory & Monitoring Network

SJRRIP: San Juan River Basin Recovery Implementation Program

UDEQ: Utah Department of Environmental Quality

UDWQ: Utah Division of Water Quality

UDWR: Utah Department of Wildlife Resources

USEPA: United States Environmental Protection Agency

USFWS: United States Fish and Wildlife Service

USGS: United States Geological Survey

USU: Utah State University

VUS: NPS Visitor Use Statistics

WRD: Water Resources Division

Glossary

Condition Assessment: A condition assessment reports on the *current condition* of one or more *indicators of condition* for a given resource. A resource topic is selected as a condition assessment when enough data are available to inform current condition of selected indicators, which are evaluated by using scientifically justifiable *condition rating statements*. What constitutes "enough" data is a professional judgement based on a review of all available data and discussion with park staff, subject matter experts, and researchers involved in collecting the applicable data. Condition is evaluated for each indicator using a 5-level rating system, ranging between good-fair-poor; if trend can be reported for an indicator, it is reported as improving, stable, deteriorating, or unknown/indeterminate.

Condition Rating Statements: These correspond to the five-level rating system developed for the indicators of condition. The five levels are good, good/fair, fair, fair/poor, and poor, with corresponding "stop light" colors. Condition ratings statements are developed at the indicator level for the combination of measures evaluated for each indicator. The statements must be logical and defensible based on the best available science.

Confidence Level: These correspond to a three-level rating system of low–medium–high described for the indicators of condition rating evaluation. These levels are based on the repeatability of evaluation findings and how confident the author is in the information used to evaluate condition.

Current Condition: This defines the status of condition for an indicator based on the accumulation of one or more measures. "Current" applies to the condition as it exists today, based on what has previously occurred, not on what is likely to occur. Something such as level of hazard or risk, which identifies the potential or likelihood of what may occur due to the intrinsic characteristics of the resource, will not be used to report on current condition**.** In general, data collected within the last ten years can be used to determine current condition, although this will depend on the rate of change for a particular indicator and its corresponding measures.

Data Gap: A resource is listed as a data gap when information is lacking, or expertise is needed to adequately evaluate condition. One key difference between a data gap and a gap analysis is the level of information reported.

Driver: Ecosystem drivers are major (and most often) external influencers of change to natural systems, functioning across large areas or scales. Drivers are defined as "any relatively discrete events in space and time that disrupt ecosystem, community, or population structure and change resources, substrate, or the physical environment (White and Pickett 1985)." Drivers are most often beyond a manager's ability to influence or change.

Gap Analysis: A gap analysis is a summary of what is known about a given resource in addition to what information is lacking rather than reporting on an indicator of condition. These information gaps are summarized in a table of *potential* indicators, measures, and reference criteria with the goal of providing a framework for a future study.

Indicator: An indicator is a descriptor of something useful to measure, but it is not the measure itself. Indicators should be specific, measurable, and sensitive to change. Status of current condition for a condition assessment is assigned at the indicator level. This is because resources are often more complex and nuanced than what is reflected in just a few measures. In a gap analysis, these are listed as *potential* indicators with no condition assigned to them.

Measure: A measure is either qualitative or quantitative and provides the specific information about the indicator. There can be one or more measure(s) for each indicator. Selected indicators and measures are often those that are commonly used by NPS staff in monitoring the status of a resource, as well as those that are well represented in the literature and can provide context when park-specific data are lacking. In a gap analysis, these will be listed as *potential* measures.

Pressure: A pressure is a result of a driver that potentially affects a resource. An NRCA presents drivers and pressures as the fundamental forces that play important roles in regulating or altering ecological resource conditions in the park and does not differentiate between the two.

Reference Criteria: Reference criteria are pivot points, thresholds, or ranges based on peer-reviewed literature, state standards, known criteria, or some other justifiable source of information. Quantitative reference criteria are generally better than qualitative reference criteria, but when specific data are lacking, qualitative reference criteria are useful. Regardless of the type of reference criteria used, they must be justifiable. In a gap analysis, these will be listed as *potential* reference criteria.

Response: Management implications and useful near-term actions/activities park managers can consider to protect, maintain, and/or restore important ecological resource conditions in parks.

State (Condition): The "health" or condition of the resource reported at the indicator level. Refer to the definition for Current Condition above.

Stressor: "Stressors can manifest as physical, chemical, or biological perturbations to a system that are either foreign to that system, or natural to the system, but occurring at an excessive or deficient level. Stressors cause significant changes in the ecological components, patterns, and processes in natural systems. They act together with drivers on ecosystem attributes (Barrett et al. 1976)." When possible, stressors are selected as measures with which to evaluate current condition of an indicator.

Natural Resource Condition Assessments – Introduction

The National Park Service's (NPS) Natural Resource Condition Assessment (NRCA) Program evaluates natural resource conditions in park units and delivers the results to park staff, scientists, strategic planners, and the general public through reports and associated products. All NRCA efforts strive to report resource condition information that informs multiple levels of park stewardship activities. Stewardship activities may include partnerships, resource stewardship plans, park management plans, and may inform on-the-ground actions that park management can implement.

As part of the NRCA program, Natural Resource Condition Assessments (NRCAs) are one-year projects designed to provide efficient, yet defensible, "status of knowledge" information on drivers and stressors, current conditions, and critical data gaps for a limited number of important park ecological resources. NRCAs are intended to use the best available scientific data for park-selected focal resources, drivers, stressors, and manager questions or needs. This body of scientific information is synthesized, analyzed, and interpreted using appropriate study methods and techniques. A manager-scientist team of experts considers the overall reasonableness and defensibility of study findings, management implications associated with those findings, and useful responses that park managers may consider to further understand, maintain, and/or improve natural resource conditions.

Standard products from NRCA projects include a detailed project report and associated products. These may include species checklists, geospatial maps and data, presentations, and others. All reports and associated products are available via the NPS Datastore (https://irma.nps.gov/DataStore/).

Conceptual Framework for Assessing Resource Conditions and Influences

NRCA projects employ a Drivers, Pressures, Stressors, States, and Responses (DPSSR) conceptual framework (Figure I-1) similar to that used and advocated by others (Office of National Marine Sanctuaries 2020; Harwell et al. 2019). The DPSSR framework structures the content in an NRCA report and guides discussions of the anthropogenic and/or natural factors that "drive" ecosystem change. The effects of a driver or pressure (hereafter referred to as driver) may affect the current condition (or state) of a natural resource indicator as a positive or negative stressor. For stressors within the park's "span of control", a park management response may maintain, improve, or restore the natural resource indicator of condition to a desired state. For stressors the park can't directly manage or influence, it's still helpful to understand potential impacts, especially when identifying realistic management goals.

It's important to note that an NRCA project does not report on all natural resources for a park. Instead, the NRCA Program or park managers may use the DPSSR framework to guide the evaluation of new natural resource conditions or to re-evaluate conditions in future NRCAs, especially as drivers or stressors change or as new information becomes available.

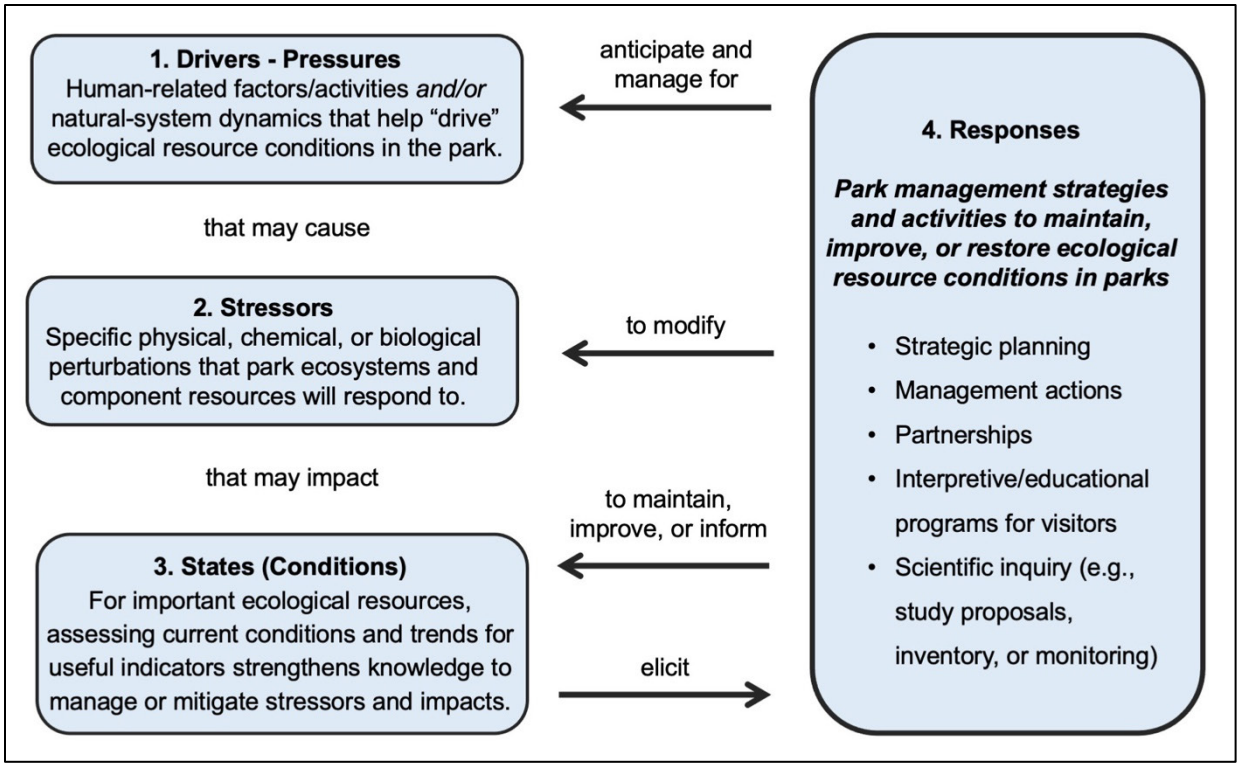


Figure I-1. The DPSSR conceptual framework is used to report drivers, stressors, states, and responses in NRCA projects (adapted from Harwell et al. (2019) and the Office of National Marine Sanctuaries (2020)).

NRCA Technical Report

NRCA projects are developed in five phases: project initiation, study plan scoping, study plan development, technical report development, and project finalization. During the initiation and study plan scoping phases, park managers select the subset of important focal natural resources that will be evaluated with respect to their conditions/states. Park managers also identify specific management questions and information needs they hope can be addressed in the study. During the study plan scoping and development phases, the focal resource drivers and stressors are identified and then reported in the technical report's Chapters 2 & 3. Management responses and considerations that help protect, maintain, and/or improve the focal natural resource conditions or to inform critical data gaps are reported in Chapter 4.

Focal Resources and Drivers & Stressors Summary for GLCA's NRCA

Glen Canyon National Recreation Area (GLCA) managers selected the less-studied non-Colorado riverine water-dependent environments and organisms that rely on those environments as the focal resources for the park's NRCA. The primary drivers and stressors influencing the conditions of those resources are listed in Table I-1, using the Conservation Measures Partnership (2016) *Classification of Conservation Actions and Threats* categories and terminology. The classification defines a common nomenclature to support collaboration among conservationists and consistency across NRCA reports.

Table I-1. The primary drivers-pressures and stressors influencing the conditions (states) of GLCA's focal resources. The categories are from the Conservation Measures Partnership (2016) classification.

Drivers-Pressures ***Fundamental Forces to Consider***	**Stressors** ***Potential Influences to Consider***
Agriculture	Livestock farming & ranching, including irrigation
Energy Production & Mining	Power-plant air-borne pollution
	Resource exploration & extraction
Biological Resource Use	Fishing
Human Intrusion & Disturbance	Visitor-caused fire & trampling
	Off-road vehicle use (noise & dust pollution)
Invasive & Problematic Species, Pathogens, & Genes	Problematic animals, insects, diseases, parasites, & plants
Natural Systems Modification	Altered hydrology
	Water contaminants
	Geohazards (e.g., rockfall)
Climate Change	Changes in temperature & precipitation regimes

Summary of Needed Changes to the GLCA NRCA report.

1. Replace NRCA Introduction with text & table above.
2. Add (see Table I-1 for a summary) to the first paragraph in CH 2.
3. Delete paragraph 2.1.
4. Delete table 2.1-1.
5. Renumber all headings, figures, and tables in CH 2, including in-text references.
6. Update all TOC for correct page, figure, and table numbering.

Chapter 1. Introduction to Park Setting and Resources

Glen Canyon National Recreation Area (GLCA, NRA, park) is one of 18 national recreation areas included in a system of 423 national parks. It was congressionally legislated in 1972 to "provide for public enjoyment through diverse land- and water-based recreational opportunities, and protect scenic, scientific, natural, and cultural resources on Lake Powell, the Colorado River, its tributaries, and surrounding lands" (GLCA Act 1972; Public Law 92-593, 86 Stat. 1311). GLCA is co-managed with the 64.7-ha (160-ac) Rainbow Bridge National Monument (NM), which was established in 1910 to protect a large and scenic natural bridge and surrounding area. Both the NRA and NM are administered by the National Park Service (NPS), which is one of nine bureaus and offices of the Department of Interior (DOI) that manages America's vast natural and cultural resources for the enjoyment and use of future generations.

1.1. Location

GLCA is situated in the Colorado Plateau region of northern Arizona and southeastern Utah, approximately 439 km (273 mi) north of Phoenix, Arizona and 636 km (395 mi) south of Salt Lake City, Utah (Figure 1.1-1). It encompasses more than 0.5 million ha (1.25 million ac), 51% of which is identified as proposed or potential wilderness (NPS 2014). The park extends over 322 km (200 mi) from southern Utah's Green River to its southern end at Lee's Ferry in northern Arizona. Park headquarters is located in Page, Arizona—the local gateway for Lake Powell recreation.

A scenic vista overlooking Farley Canyon in GLCA. Image Credit: NPS.

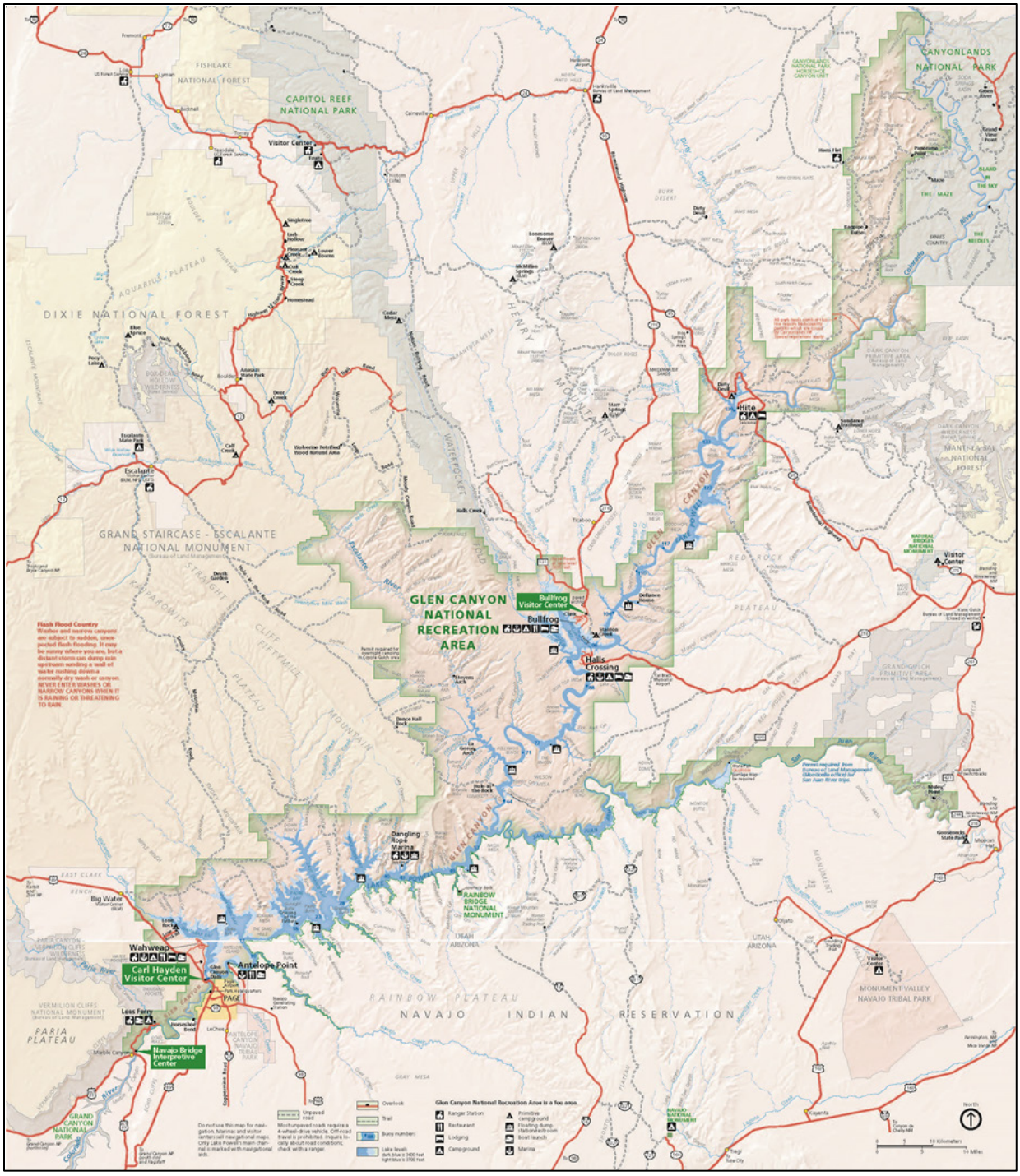


Figure 1.1-1. NPS map of GLCA and surrounding region. Figure Credit: NPS/Harpers Ferry Center.

GLCA is surrounded by 96.75% of federal lands within an area of 30,852 km^2 (11,912 mi^2), which is a 30 km^2 (18.6 mi^2) ecological buffer that supports most species' life cycles (Monahan et al. 2012). Of the federally managed land, 65.1% is classified as United States Geological Survey's (USGS) protected areas Gap Analysis Project (GAP) Status 3, which allows for a variety of activities, sometimes intense, such as mining but protects the land from major development (USGS 2018).

1.2. Setting and Resources

The Colorado Plateau Physiographic Province, which encompasses an area of 386,242 km^2 (240,000 mi^2), is characterized by its colorful and relatively un-deformed geology, as characterized by its relatively flat-lying sedimentary rock, and high desert arid climate that has formed the region's present-day topography and soils (Glen Canyon Institute 2017). The province is divided into six sections, and GLCA is primarily situated in Canyonlands—an area known for its spectacular displays of sandstone and shale features—but a small portion in GLCA's southern end is located in the High Plateaus of Utah, with the Kaiparowits Plateau transitioning between the two sections (Banner 1992). GLCA's lowest elevation is at Lee's Ferry, which lies close to 975 m (3,200 ft) mean sea level (msl), whereas the highest points in the park are found on the Kaiparowits Plateau at 2,310 m (7,580 ft) (mid-park) and in the Orange Cliffs area in southern Utah at the northern end of the park at 2,134 m (7,000 ft) msl. This range of elevation creates "some of the most rugged and remote backcountry within the Colorado Plateau" (Thomas et al. 2005) where wind and water, with influences from the Colorado River and its tributaries, have carved an array of deep canyons, buttes, mesas, and other features such as tinajas, natural bridges, and arches.

Rainbow Bridge National Monument is remote and cannot be accessed by vehicle. Image Credit: NPS.

1.2.1. Colorado River

The Colorado River flows through the heart of the Colorado Plateau, stretching 2,330 km (1,450 mi) from its headwaters in Colorado's central Rocky Mountains to Mexico near the Gulf of California.

The river and its tributaries are extensively controlled by dams, reservoirs, and aqueducts primarily for domestic water supply and agricultural purposes. The mainstem of the Colorado contains 15 dams, including the Glen Canyon Dam, which was completed and operational in 1966, forming the second largest reservoir in the United States: Lake Powell. The Colorado River flows for approximately 42 km (26 mi) in the northeast end of the park before it widens and enters Lake Powell, which comprises only 13% of GLCA's total land area when the reservoir is full. Over the course of its first 17 years post-construction, Lake Powell reached its full pool level of 1,128 m (3,700 ft) above sea level (NPS 2015). As the Bureau of Reclamation manages the outflow at the dam and the corresponding water levels, the size of Lake Powell fluctuates between 21,000–66,000 ha (51,892–163,090 ac), and the length of shoreline increases and decreases concomitantly. As a result of the reservoir filling what was originally "Glen Canyon" and inundating the surrounding landscape, most of the lake's shoreline consists of uneven terrain, steep slopes, and sandstone cliff walls.

1.2.2. Complex Desert and Water Environments

The rivers that flow into GLCA and Lake Powell include the Colorado and its tributaries—the San Juan, Dirty Devil, and Escalante. The Paria River enters the park and Colorado River 25 km (15.5 mi.) below Glen Canyon Dam just before entering Marble Canyon and then Grand Canyon. These river systems and associated wildlife and plants are situated in areas of deeply incised, cliff-lined watersheds, and within these sandstone canyon-walled watersheds, numerous perennial and intermittent streams and springs occur off of the primary rivers, forming oases of riparian, wetland, and spring habitats. The interplay between the porous geologic layers, arid desert, and river-fed water environments support a unique and diverse assemblage of vegetation and wildlife that are highly dependent on the water cycles and sources of the Colorado Plateau. These cycles and sources are complex but vital, because so little precipitation is received, and such high evaporation and evapotranspiration rates occur during the summer.

GLCA is a semiarid environment characterized by hot summers and cold winters, with high spatiotemporal variability in precipitation and temperature (Tendick et al. 2017) due to the park's wide longitudinal and altitudinal ranges (Spence 2001). Winter temperatures often dip well below freezing for extended periods, while summer temperatures can reach as high as 38°C (110°F) (Tendick et al. 2017). Lees Ferry, at 978 m (3,208 ft), receives approximately 153 mm (6 in) of precipitation per year while the Escalante climate station, at 1,776 m (5,827 ft), averages 278 mm (11 in) per year (Spence and Cushing 2019). Although precipitation is variable, the general pattern is weakly bimodal, with the largest peak occurring during the late summer monsoon (30–35% of total annual precipitation) and a smaller peak occurring in late winter (Spence and Cushing 2019).

During the summer monsoon period, rain events often occur as intense, but short-lived thunderstorms. Occasionally, longer duration rainstorms occur as remnants of Pacific hurricanes or tropical storms that pass over during the summer and fall seasons. Northern fronts and Pacific storms also occasionally bring snow during the winter, but for the most part, only leave snow accumulations in the "inches" except for the higher elevations above 1,829 m (6,000 ft) msl. Of the types of

precipitation received, winter snowmelt is the primary contributor to groundwater recharge and soil moisture, providing deep soil infiltration (Spence 2001).

Over decades, precipitation events have promoted the formation of biotic soil crusts, which help to stabilize soil surfaces. Desert cool and warm season grasses, shrubs, a few cold-hardy scattered cacti, and pinyon pine (*Pinus edulis*) or Utah juniper (*Juniperus osteosperma*) trees try to quickly uptake any available precipitation. Thousands of rain-carved tinajas (also called waterpockets, ephemeral pools, and potholes) are formed in the sandstone slickrock and collect rainwater and snowmelt to serve as short-lived oases to wildlife and even some aquatic insects. The large expanses of the Navajo Sandstone and other porous sandstones absorb water during the storms that then may flow through the rock until it encounters cracks or denser layers of stone, reappearing on the face of sandstone cliffs as seeps (GLCA, K. Hyde, NPS Chief of Science and Resource Management, review, 19 April 2021). These seeps then provide water to a myriad of unusual plants, many of which are wetland obligates, in small hanging gardens in the alcoves or "glens" and along the cliff faces. Small springs and seeps also appear at the base of the sandstone cliffs or in the nearby washes and host a diverse array of obligate and facultative wetland plants in areas that cannot be accessed by livestock or scoured by flash floods. The environmental conditions in the glens are typically cooler and moister due to the shading effect of the steep canyon walls in sharp contrast with the upland desert environment, thereby serving as "biodiversity hotspots" (Cartwright et al. 2020).

View of Gunsight Butte and Navajo Mountain form Alstrom Point in Lake Powell. Image Credit: NPS/Brent & Dawn Davis.

1.2.3. Flora & Fauna

Tendick et al. (2017) mapped a total of 505,642 ha (1.25 million ac) of vegetated (75% of the area) and non-vegetated (25% of the area) classes throughout GLCA. The non-vegetated classes include rivers and lakes (47,785 ha/118,079 ac) and small to extensive areas of bare sandstone/slickrock (74,339 ha/183,696 ac), which comprise almost all (96.9%) of the unvegetated areas. Even with one quarter of GLCA's area classified as unvegetated, it is identified as one of the most floristically diverse parks on the Colorado Plateau, with 865 taxa recorded as of 2017 (Tendick et al. 2017).

In general, following an elevational gradient from high to low, GLCA's flora is dominated by upland desert vegetation, including woodlands and shrublands, and by the less dominant but more biologically diverse wetland communities. The wetland habitats are partially comprised of obligate phreatophytes in areas that are periodically flooded or where groundwater is shallow (Spence 1996b). These include riparian areas along streams and rivers, with a high disturbance regime; marshlands, which are permanently saturated and occupy low-lying areas; springs and seeps, as well as other geographically isolated water resources (e.g., tinajas) that support hundreds of plants, many of which are endemic or relict species (Springer et al. 2006). Tinajas are often located in active drainages that can form into very large, deep, year-round water sources, whereas potholes, ephemeral pools, and waterpockets are more shallow depressions in eroded bedrock on flat or slightly dipping surfaces. The shallower bedrock depressions are typically smaller than tinajas, as well as ephemeral, and as a result do not support as many aquatic lifeforms as those found in other water-holding features or habitats throughout the park. Nevertheless, they are still important resources for wildlife, particularly in an arid environment.

Immigrant spring in Silver Falls Canyon, Escalante District, Leopard frog in Bowns Canyon, and narrow bedrock riparian habitat in Harris Wash, Escalante District. Image Credits: NPS.

Fauna of the Colorado Plateau is primarily limited by water availability and vegetation diversity (Thomas et al. 2006). Thus, areas supporting the highest species richness are the water-dependent environments such as riparian corridors, springs, seeps, and tinajas, which provide important habitat for a suite of terrestrial and aquatic invertebrates (Springer et al. 2006); numerous species of amphibians (Nowak and Persons 2008); breeding and migratory birds, and a variety of mammals, ranging in size from rodents and bats to large ungulates and predators, including desert bighorn sheep (*Ovis canadensis nelsoni*) and cougars (*Puma concolor*) (Cartwright et al. 2020; Spence et al. 2011). Of the fish species present in GLCA, only 30% of the total number are native, and all but one, speckled dace (*Rhinichthys osculus*), are rare (NPSpecies 2020). These natives primarily occupy the Paria, Escalante, San Juan, and Dirty Devil rivers and their tributaries, although small populations also exist in the Colorado River above and below the dam and reservoir, and similar to the park's other fauna, are highly dependent on the availability of water and timing of precipitation for survival.

Eastwood's monkeyflower. Image Credit: NPS.

Chapter 2. Drivers and Stressors

Chapter 2 summarizes select primary driving forces (drivers) and the physical, chemical, and biological disturbances (stressors) (see Table I-1 for a summary) of the selected focal resources. For streamlining purposes, drivers and pressures are not differentiated throughout the report, and when stressor-related data are available (e.g., non-native invasives, water contaminants), they are used as indicators of condition and/or measures to evaluate the states of park-selected focal natural resources in Chapter 3.

2.1. Human History

People have been interacting with the resources of GLCA and surrounding Colorado River region for more than 10,000 years (NPS 2014). Ancestral Puebloan historic and pre-contact structures have been identified throughout the national recreation area, and 19 present-day American Indian tribes and bands are the "contemporary descendants" of those who previously inhabited the area. These lands are sacredly connected to the American Indian tribes and bands' ceremonial activities, cultural practices, and histories (NPS 2014). Additional structures and cultural landscapes throughout GLCA preserve evidence of Spanish explorers from the 1600s and 1700s; the local history of The Church of Jesus Christ of Latter Day Saints after their migration to and expansion throughout the West starting in 1847; the exploration for and extraction of minerals by American Indians and miners; and livestock management by both American Indians and Anglo ranchers. However, to date, only 3% of GLCA has been surveyed for cultural resources (NPS 2014), and it's likely that some of the un-surveyed sites have been permanently erased from the historic record due to the inundation of the landscape by the filling of Lake Powell. In addition, the formation of the lake has created an almost unlimited number of access points throughout the park, increasing cultural and natural resource damage, either intentionally or inadvertently, especially by boaters (NPS 2014).

2.2. Visitor Use & Recreation

In 2019, GLCA recorded its second highest number of recreation visits at 4,330,563 since counting began in 1964, ranking 19th in the NPS (4th highest of all NPS national recreation areas). In 2017, its highest number of recreation visits was 4,574,940 (NPS Visitor Use Statistics (VUS) 2020a). Land- and water-based activities are offered throughout the year at GLCA, but water-related recreational activities are most popular from April–October, although March and November can receive high numbers of visitors as well (NPS VUS 2020b). Out of GLCA's seven districts reporting 2019 visitor counts, the Wahweap District comprised 68.9% of the total. The next highest count reported was in the Horseshoe Bend District at 12.4%. Both the Wahweap and Horseshoe Bend districts are located near Page, Arizona, although the former district extends north into southern Utah (NPS VUS 2020c).

Kayaking on Lake Powell, GLCA. Image Credit: NPS.

Nationwide, Arizona and Utah rank as the 4th and 5th highest states, respectively, for NPS-related visitor spending (Cullinane and Koontz 2020). It's estimated that $420 million was spent in 2019 by the 4 million plus visitors in the local gateway region surrounding GLCA, with 96.3% of spending made by non-local visitors (Cullinane and Koontz 2020). Services include lodging, restaurants, and recreational outfitters (Cullinane and Koontz 2020). This represents a 265% regional spending increase since 2012. Much of the local development supports access to Lake Powell, including

marinas, airports, campgrounds, and boat rentals. While GLCA is comprised of many backcountry opportunities, visitors are concentrated in the Wahweap and Horseshoe Bend districts where there are few shoreline areas offering lake access by vehicle, especially given the uneven terrain and steep slopes of the flooded landscape (NPS 2018). The high visitor uses of Lake Powell, including houseboating, boating, jet-skiing, swimming, fishing, and overnight camping, has contributed to the introduction and spread of non-native invasive species including fish, mussels, and plants; poor water quality (associated impairment data were provided by Dean Tucker, NPS Water Resources Division, and are presented in Chapter 3); trampling and destruction of cultural and natural resources; and human-ignited fires in a region unadapted to fire.

2.3. Non-native Invasive Plants and Vegetation Transitions

During GLCA's vegetation mapping project, 86 non-native invasive vascular plant species, or 11.2% of the total number of vascular plants, were reported (Tendick et al. 2017); NPSpecies (2020) reports 87 non-native plants as present, three as unconfirmed, and 12 as probably present. Eleven of these are on the State of Utah Noxious Weed List (Utah Department of Agriculture and Food 2019) and seven are on the Arizona State-listed Noxious Weeds list (USDA NRCS 2020) for a total of 14 species (Table 2.1.3-1). Hill and Ayers (2009) included several additional non-native invasive plants of concern listed by the Southwest Exotic Plant Mapping Program that are not included on either list for Utah or Arizona due to the agricultural focus of those state-listed species.

Park efforts to manage targeted species, including Russian thistle (*Salsola kali*), Russian olive (*Elaeagnus angustifolia*), Russian knapweed (*Acroptilon repens*), tamarisk (*Tamarix ramosissima)*, camelthorn (*Alhagi maurorum*), black locust (*Robinia pseudoacacia*), perennial pepperweed (*Lepidium latifolium*), Dalmatian toadflax (*Linaria dalmatica*), ravenna grass (*Saccharum ravennae*), and mullein (*Verbascum thapsus*), have occurred over the last 20 years (Tendick et al. 2017). Also, in 2004, the highly invasive Sahara mustard (*Brassica tournefortii*) appeared at Lees Ferry and subsequently spread to Lake Powell shorelines. Many of the management focus areas include high vector zones, such as along roads and highways and along Lake Powell's shoreline and riparian zones (refer to the riparian zone and springs & seeps condition assessments for specific details about non-native invasive plants in those environments).

With rising temperatures and more frequent droughts occurring, one of the questions resource managers posed was "What new non-native invasive plants should they anticipate if climate conditions continue to shift to desertification?" According to Jodi Norris, Landscape and Quantitative Ecologist with the NPS Southern Colorado Plateau Inventory & Monitoring Network (SCPN), two issues complicate predictions of ecosystem response to climate change. First, there are large distances between GLCA and ecosystems that might provide plants or animal genotypes adapted to future mean annual temperatures. Currently, these are in places like the southern parts of Nevada, Arizona, and California, with the Mogollon Rim and other extensive mountains and canyons between them and GLCA. However, the low-elevation Colorado River corridor likely provides a path for some hot desert species such as mesquite (*Prosopis* spp.) and catclaw (*Acacia greggii*).

Table 2.3-1. Non-native plant species that are in GLCA and listed on Arizona and/or Utah state noxious weed lists.

Species	NPSpecies (2020) Occurrence	Arizona State Noxious Status [2]	Utah State Noxious Status [3]
Acroptilon repens	Present	PNW, RNW	Class 3
Brassica tournefortii	Present	–	Class 1B
Convolvulus arvensis	Present	PNW, RGNW	–
Cynodon dactylon	Present	–	Class 3
Elaeagnus angustifolia	Present	–	Class 4
Elymus repens	Present	RNW	Class 3
Halogeton glomeratus	Present	PNW, RNW	–
Lepidium latifolium	Present	–	Class 3
Linaria dalmatica	Probably present [1]	RNW	Class 2
Portulaca oleracea	Present	PNW, RGNW	–
Salvia aethiopis	Probably present	–	Class 1A
Sorghum halepense	Present	–	Class 3
Tamarix ramosissima	Present	–	Class 3
Tribulus terrestris	Present	PNW, RGNW	–

[1] This plant has been actively managed at the park but not vouchered.

[2] PNW = prohibited noxious weed, RNW = restricted noxious weed, RGNW = regulated noxious weed

[3] Class 1A is an **Early Detection Rapid Response (EDRR)** watch list of plants not known to exist in Utah but that pose a serious threat and are very high priority.
Class 1B is an **EDRR** watch list of plants known to exist in very limited populations in Utah and pose a serious threat and are very high priority.
Class 2 is a **Control** watch list of plants that exist in varying population sizes where control of eradication may be possible.
Class 3 is a **Containment** watch list of plants that are widely spread where efforts may reduce or eliminate new or expanding populations.
Class 4 is a **Prohibited** watch list of plants pose a threat through the retail sale or propagation in nurseries or greenhouses.

The second issue is that once summer and winter temperatures are factored in (instead of using the very broad measure of mean annual temperature), there are no places in the western U.S. that currently have the approximate combination of seasonal temperatures that GLCA is projected to have. This is largely because its position on the Colorado Plateau means that it will still be subject to cold winter temperatures, unlike potential analogues in southern parts of Nevada, Arizona, and California. Non-analog climates create a problem for predicting ecosystem responses, because species distribution models are based on the current suite of climatic conditions and can't be used to predict whether a species will be able to adapt to novel conditions (Fitzpatrick and Hargrove 2009). Estimations based on plant functional group models suggest that future conditions may lead to greater dominance of shrubs relative to grasses in a variety of western ecosystems, including those at GLCA (Gremer et al. 2018; Spence 2017). Recent years of record high temperatures suggest changes are already occurring, and plant water stress is consistently predicted to increase due to increasing

temperatures (Andrews et. al. 2019; Spence and Cushing 2019), which increases evaporative demand.

Utah Conservation Corps work crew for Russian olive removal along the Escalante River. Image Credit: NPS.

The loss of cool season grasses under the current climate conditions is further exacerbated by grazing impacts, which promotes areas of bare soil easily inhabited by common weedy species like cheatgrass (*Bromus tectorum*), Mediterranean grass (*Schismus* spp.), and Russian thistle. However, species like cheatgrass also rely on cool season and spring moisture so may not thrive as well with changing climate. With the Lake Powell reservoir at less than 50% capacity, there are large expanses of bare soils left open to colonization by Russian thistle, thereby creating ideal habitats for this species to spread rapidly into other open habitats during its "tumbleweed" phase each fall and winter. Off-road vehicles (ORV) and livestock continue to spread weeds picked up on tires and hooves or consumed from existing stands of noxious weeds that are then transported and dropped into new areas already impacted by a changing climate. The park will continue to monitor and treat the high threat invasive species, but just may have to sit back and observe significant changes in species composition and non-native species expansion as climatic changes impact hundreds of thousands of

acres in already fragile, high desert environments (GLCA, J. Spence, Deputy Chief for Natural Resources & Chief Scientist, review, 11 December 2020).

Unnatural levee along the Escalante River as a result of Russian olive. Image Credit: NPS.

2.4. Ranching & Livestock Management (Grazing)

Beginning in the late 1700s, livestock grazing of sheep, goats, cattle, burros, and horses began in the area of present-day GLCA, creating impacts to resources unadapted to continuous and heavy livestock use. In 1972, when the U.S. Congress established GLCA as a national recreation area, they directed the Bureau of Land Management (BLM) to administer continued grazing use by designating allotments. Twenty-eight of those allotments allow grazing in areas that are entirely or partially within GLCA (BLM 2015), representing 60% of the park (over 28,328 ha/700,000 ac). As of 2015, seven of the 28 allotments did not meet rangeland requirements, particularly for springs and riparian areas (BLM 2015). Additionally, impacts from feral animals, including cattle, horses, and burros are also occurring in areas of the park. Many of these animals range in and out of GLCA in very remote locations, so developing management solutions can be difficult. In addition, The Wild Free Roaming Horse and Burros Act (1971) adds an additional level of complexity that managers must address as they work with BLM to ensure compliance and consideration of the Act during any joint planning effort.

Impacts from grazing, coupled with less than ideal land management practices and prolonged droughts have resulted in resource degradation, especially to water sources, native grasslands, and biological soil crusts (Tendick et al. 2017). In addition, research conducted near Canyonlands National Park (NP) found that livestock grazing can lead to declines in soil nutrients (Neff et al. 2005), further intensifying the often slow and incomplete recovery of native grasslands from grazing impacts.

Different locations at East End Spring on Navajo Point, showing effects of grazing (left, September 2001) and no grazing (right, August 2005). Image Credits: NPS.

2.5. Air Quality (Pollution)

Air pollutants, deposited through rain and snow (wet deposition) or dust and gases (dry deposition), can have a variety of negative effects on ecosystem health, including acidification, fertilization or eutrophication, changing soil pH, which in turn affects microorganisms, understory plants, and trees (NPS Air Resources Division [ARD] 2010). Simkin et al. (2016) evaluated the influence of nitrogen deposition on plant diversity across the U.S. by sampling soil chemistry across ambient nitrogen gradients between plant communities. One of their focus areas was in the Southern Colorado Plateau, including one, open canopy site at GLCA. They selected this region due to the fact that coal-fired power plants have emitted elevated levels of nitrogen oxides (NO_x) over prolonged periods of time.

Simkin et al. (2016) found that grasslands, shrublands, and woodlands were more susceptible to species loss at lower critical loads of nitrogen than forests, and that the loss of diversity increased as soils increased in acidity. The role of temperature and precipitation in nitrogen deposition helped to explain species richness, but the influence was less consistent across the scales of analyses as compared to vegetation types or pH (Simkin et al. 2016). These results are consistent with Sullivan et al. (2011a,b), who rated GLCA ecosystems as highly sensitive to nitrogen-enrichment and acidification effects relative to all Inventory & Monitoring Network parks.

Increases in nitrogen deposition, coupled with grazing impacts to soils and vegetation, promote invasions of fast-growing non-native annual grasses (e.g., cheatgrass) and forbs (e.g., Russian thistle) at the expense of native species (Brooks 2003; Schwinning et al. 2005; Allen et al. 2009). Increases in non-native annual grasses can increase fire risk (Rao et al. 2010), with profound implications for biodiversity in non-fire adapted ecosystems, such as GLCA. Nitrogen may also increase water use in plants like big sagebrush (*Artemisia tridentata*; Inouye 2006).

Although air quality across the U.S. has improved over the last several decades, there are still major concerns regarding pollutants in the U.S. (USEPA 2020). According to the U.S. Environmental Protection Agency (USEPA) (2020), in the United States, roughly two thirds of all sulfur dioxide (SO_2) and one quarter of all NO_x originate from electric power generation that relies on burning fossil fuels. Sulfur dioxide and nitrogen oxides are released from power plants and other sources, and ammonia is released by agricultural activities, feedlots, fires, and catalytic converters. In the atmosphere, these transform to sulfate, nitrate, and ammonium, and can be transported long distances across state and national borders, impacting resources (USEPA 2020). The National Parks Conservation Association released a 2019 study based on NPS ARD data, revealing that 96% of 417 park units exhibited significant air quality issues in at least one category of unhealthy air, harm to nature, hazy skies, or climate change (NPCA 2019). Using the NPS ARD reference criteria for wet nitrogen and sulfur deposition levels over a 5-year average (2014–2018; Taylor 2020), the conditions at GLCA were rated as fair and good, respectively, with unknown trends (NPS ARD 2020).

In recent years, many coal-burning, power-generating stations in the U.S. have shut down, leaving 20 coal plants operational in the West (Los Angeles Times 2020). A number of other coal-fired plants around the region are at various stages of being decommissioned, which should lead to better air and water quality in and around GLCA in the future. On December 18, 2020, the smokestacks of the Navajo Generating Station—the largest coal-fired plant in the Western U.S.—were demolished (The Salt Lake Tribune 2020). At its peak capacity, the station produced 2.25 gigawatts of electricity (Lustgarten 2015; Sierra Club n.d.), and "….at one time [was] the third-largest emitter of greenhouse gases in the U.S." (Bloomberg Law 2020). The station ceased operation in late 2019 but had been emitting greenhouse gases and pollutants for decades, with its smokestacks visible from Page, Arizona and GLCA's Lake Powell. Fuel for the Navajo Generating Station was provided by the Black Mesa Mine, which closed in 2005, but had withdrawn more water than the Navajo Aquifer's recharge capacity (Bloomberg Law 2020), highlighting the interrelated impacts between extraction and subsequent use of resources.

Citizen scientists participating in the Dragonfly Mercury Project at GLCA. Image Credit: NPS Air Resources Division, Dragonfly Mercury Project.

Mercury is a toxin that can also be deposited in ecosystems and can accumulate in the food chain (NPS ARD 2010; Fowler et al. 2013). In a study in the Four Corners region of New Mexico, Colorado, Arizona, and Utah, airborne mercury, or gaseous oxidized mercury, was high relative to other areas in the U.S., particularly during spring and summer (Sather et al. 2013). At Mesa Verde NP, the concentration of gaseous oxidized mercury was the highest ever recorded in the U.S. (Sather et al. 2013). However, these baseline measurements occurred prior (2009–2011) to new regulations for power plant and boiler mercury emissions (Sather et al. 2013). A follow-up study may show a decline in airborne mercury as a result of these regulatory changes (Sather et al. 2013).

In the NPS ARD's collaborative Dragonfly Mercury Project, mercury concentrations in dragonfly larvae collected at three locations (Bowns, Ribbon, and Slickhorn canyons) in GLCA were among the highest out of 100 national parks sampled from 2009–2018 (Eagles-Smith et al. 2020). In a companion study, Eagles-Smith et al. (2014) found that speckled dace sampled in 2012 at Capitol Reef NP (CARE), which shares a boundary with GLCA, exhibited the highest mercury concentrations of all fish sampled in 21 western national parks. Speckled dace is intermediate in the food chain and because mercury accumulates up the food chain, larger predatory fishes may have even higher concentrations. The authors noted that the levels observed in CARE were high enough to cause "biochemical and reproductive effects in fish, as well as reproductive impairments in birds" that prey on speckled dace (Eagles-Smith et al. 2014). Mercury in fish sampled at neighboring Grand

Canyon NP was also high, particularly considering the size class of fish sampled, but concentrations varied between the sampling sites, suggesting that mercury exposure is variable there (Eagles-Smith et al. 2014). These studies show that despite the protected status of national parks, these areas are still vulnerable to pollution originating from outside their boundaries.

2.6. Resource Extraction

Mining activities that occur near or in national parks also pose serious environmental risks, including the release of harmful substances to air, soil, and water. GLCA's enabling legislation allows for mineral extraction (GLCA Act 1972; Public Law 92-593, Sec 3), designating the BLM as the administering agency for managing leases. According to the NPS Geologic Resources Division, Glen Canyon NRA ranks 17th throughout the nation's national parks with the highest number of Abandoned Mineral Lands (AMLs) and ranks as the 3rd highest (in number) throughout the former NPS Intermountain Region (Burghardt et al. 2014). As of 2020, there are 99 AMLs at 39 sites in GLCA (Burghardt et al. 2014). Six features at three sites still require mitigation, and five of the six features are of high priority (Burghardt et al. 2014). Lastly, there are 12 Superfund sites in the Colorado Rocky Mountains, eight of which are considered by the USEPA to be the most polluted sites in the U.S. (Graham 2016). The Gold King Mine is one of those and the 2015 spill, causing contamination to the Animas River (a tributary to the San Juan River near Silverton, Colorado), underscores the potential for surface water contamination from sites that are far removed from GLCA (Graham 2016). Additionally, the complex hydrogeology of the region surrounding GLCA contributes to the increased risks of mining because without understanding how and where groundwater flows, monitoring for contamination is extremely difficult, and therefore may remain undetected until it's too late to respond effectively.

While no active wells are in GLCA, there are 25 active oil and gas wells about 19.3 km (12 mi) from the park's northeast boundary that are primarily part of the "Big Flat" field, which produces both oil and natural gas. However, most of these wells are listed primarly as oil producers. Near the southeast arm of GLCA, there are 36 active oil wells just over 8 km (5 mi) from the park's boundary. These wells are part of the "Mexican Hat" field, which is primarly an oil producing field. These wells are marginal oil stripper wells, which are either oil wells that produce under 10 barrels/day or gas wells that produce less than 60,000 ft^3 of gas/day (NPS Geologic Resources Division, Forrest Smith, Petroleum Engineer, dataset via Enverus and summary provided in email, 10 February 2021). There is little reported natural gas production associated with these oil stripper wells in the vicinity of GLCA. Furthermore, due to lower petroleum prices and large-scale extraction projects in other parts of the U.S., recent efforts to extract oil from the tar sands have been limited to date.

In addition to being an oil- and gas-rich region, the area also contains "some of the nation's highest quality uranium ore" (USGS 2020a), with thousands of abandoned uranium mines in Utah and plentiful deposits of naturally occurring uranium throughout the Colorado Plateau. In southeastern Utah, the number of abandoned uranium mines occurring on BLM land ranges from 8,000 to 11,000, many of which are within the Colorado River watershed (Graham 2016). In addition to uranium, waste from these mines includes arsenic, lead, cadmium, and zinc, and the BLM estimates 5–10% of these mines may have water quality problems (Graham 2016).

Abandoned mine entrance and tailings in GLCA. Image Credit: NPS.

2.7. Climate Change

Since 1990, the mean annual temperature in GLCA has increased ~1°C (1.5–2.0°F) (Spence and Cushing 2019). Monahan and Fisichelli (2014) found that annual mean temperature, maximum temperature of the warmest month, and mean temperature of the warmest quarter exceeded 95% of their historic range of variability (1901–2012).

John Bradford, a research ecologist with the USGS, provided downscaled climate analyses for GLCA at a 6-km (3.7-mi) resolution. Trends in annual temperature (Figure 2.1.7-1), precipitation (Figure 2.1.7-2), soil moisture, and transpiration were provided for 1915 to 2015, along with projections (2020–2100) of these variables under two standard Representative Concentration Pathways (RCPs): RCP 4.5 and RCP 8.5. RCP 4.5 represents an intermediate scenario of slowly declining greenhouse gas emissions while RCP 8.5 represents a "worst case" scenario of rising emissions (IPCC 2014).

Temperature is expected to continue rising under both RCPs, and by 2060, median temperatures will have exceeded the historical range of variation (Figure 2.1.7-1). In contrast, there have been no discernable trends in precipitation (Gonzales 2013); however, Spence and Cushing (2019) noted a slight increase in winter precipitation prior to the drought that began in 1999 and has continued on and off for over 20 years. Changes in future precipitation are expected to be far less extreme than for

temperature (Figure 2.1.7-2). Under both RCPs, precipitation is predicted to remain largely within the historical range with perhaps a small increase.

Although there are no apparent trends in precipitation, droughts have become more common in the Southwest and are expected to worsen (Lukas and Payton 2020) due to rising temperatures and increased evaporation. The current rate of warming, without any change in precipitation, will likely result in multi-decadal droughts that exceed even the driest centuries of the last 500 years by end of the 21st century (Lukas and Payton 2020). Runoff is also expected to decline by 10–30% by the end of the 21st century (Gonzales 2013). At the end of March 2021, Lake Powell was at 36% of live capacity, with April–December 2020 representing one of the driest periods on record (Bureau of Reclamation 2021).

Continued changes in precipitation patterns include less snowpack in the winter due to the occurrence of more winter rain events and hence less runoff to lower elevations during the spring; intense summer monsoons that drop large amounts of water in a short amount of time and runoff the landscape quickly; and/or seasonal changes in precipitation, such as what occurred in 2019 and 2020 where much of Arizona and the region experienced very light, if any, monsoonal rains during the hot summer months (Lukas and Payton 2020). Climatic changes in the intensity or duration of weather patterns, such as the occurrence of El Niño and La Niña over the Pacific Ocean, will also have significant impacts to the regional temperatures and precipitation events (McPhaden et al. 2021; Spence and Cushing 2019).

The capacity of species to adapt to rapid shifts in temperature and precipitation is largely unknown; however, Spence and Cushing (2019) predict that the climate of Page, Arizona will transition to one more similar to Lees Ferry, Arizona by 2100 under RCP 4.5. Under RCP 8.5, Spence and Cushing (2019) predict that Page, Arizona will become climatically similar to Las Vegas, Nevada or perhaps a hot summer day in Death Valley NP.

Even with the best climate models, uncertainty remains one of the most challenging aspects of climate change planning. Some of this uncertainty can be countered by developing a range of plausible future conditions, or scenarios (Runyon et al. 2020; see also Spence 2017). Current conditions, which is the focus of this report, can be used to inform future scenarios of climate, develop risk assessments, and set goals based on what is achievable in terms of management. Spence and Cushing (2019) developed a range of future scenarios for springs and seeps, and riparian communities. In all of them, major uncertainties include future water availability and the resilience of these ecosystems.

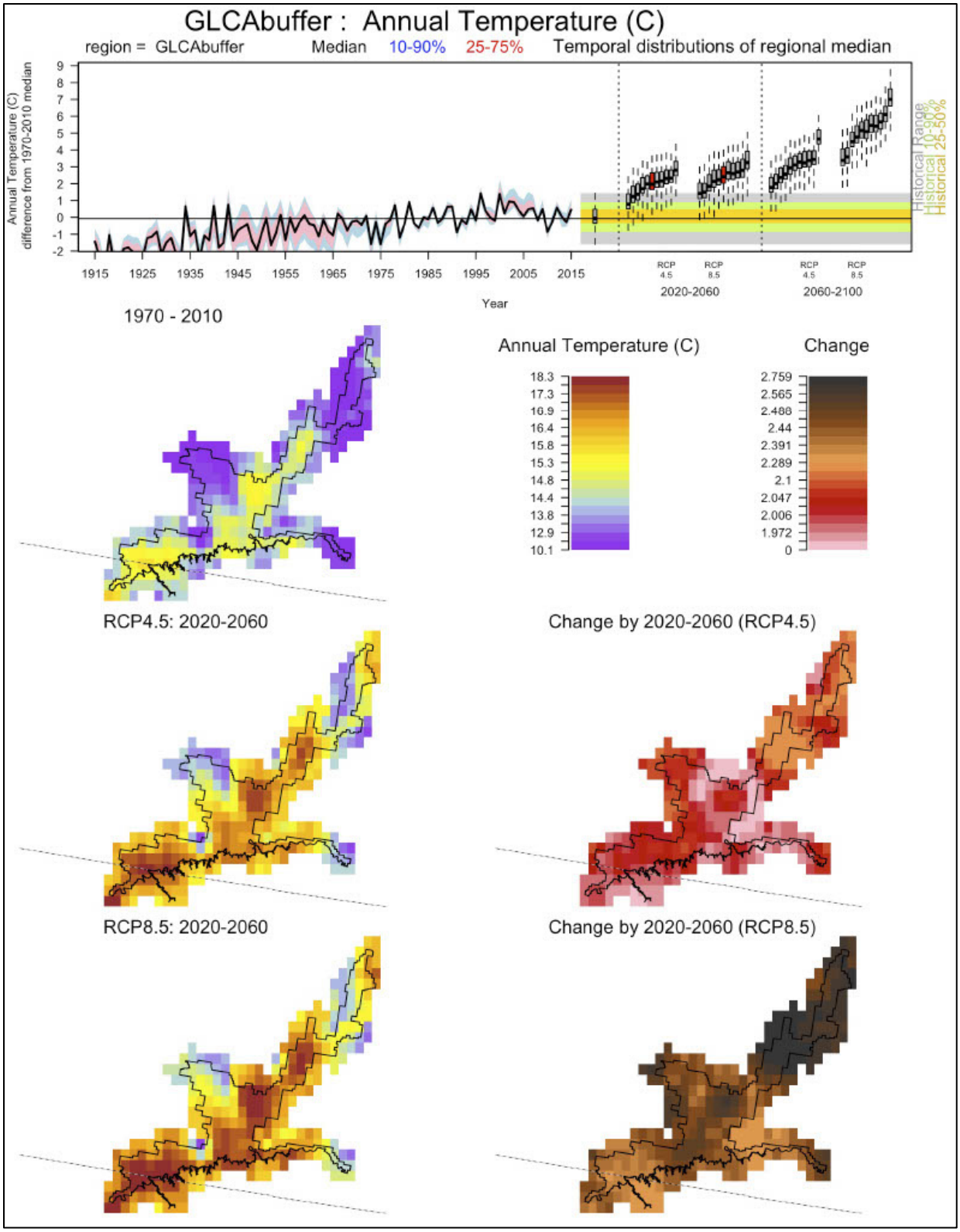


Figure 2.7-1. Historical (1915–2015) and predicted (2020–2100) departure from baseline (1970–2010) median temperature under RCP 4.5 and RCP 8.5. Figure Credit: John Bradford, USGS Southwest Biological Science Center.

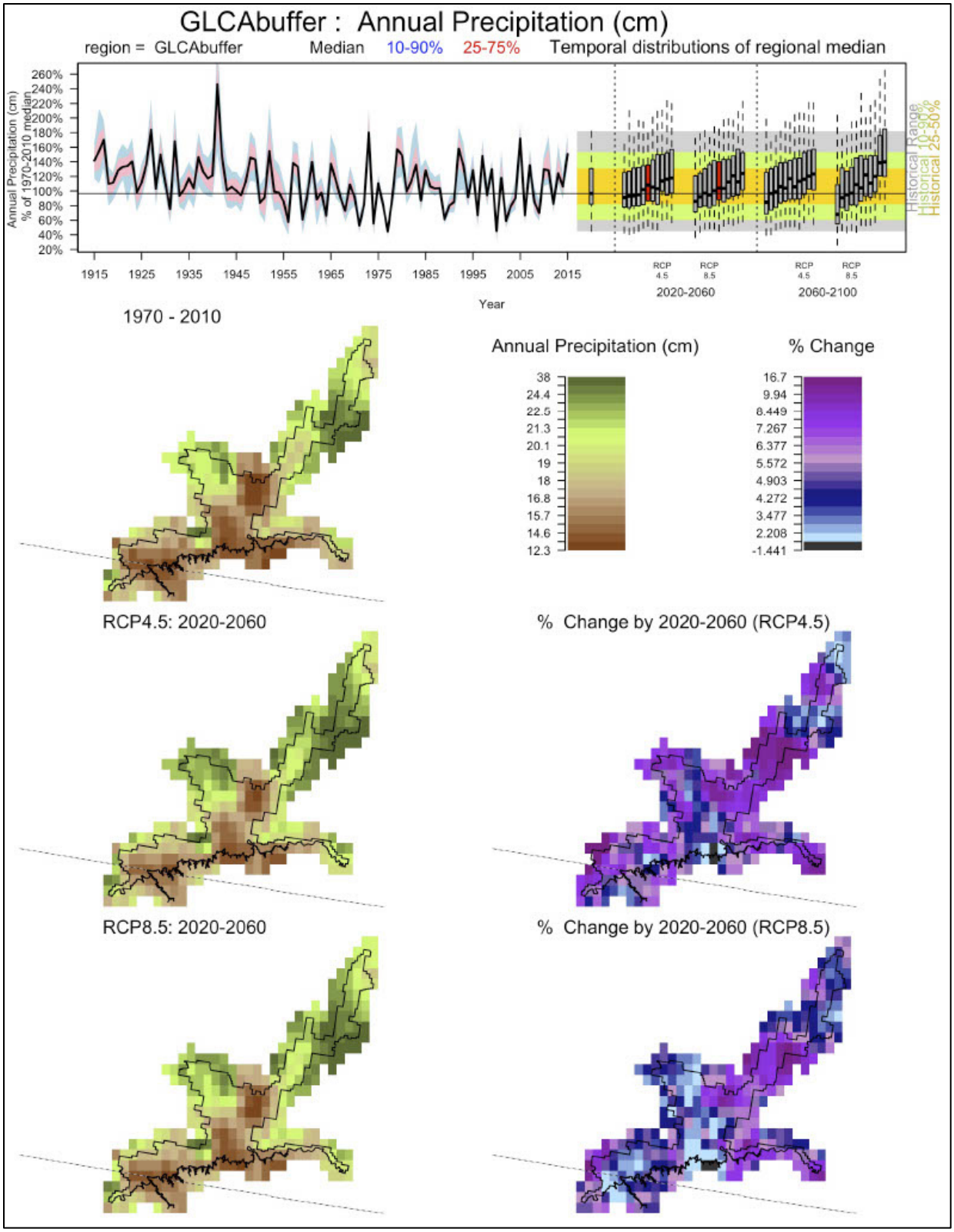


Figure 2.7-2. Historical (1915–2015) and predicted (2020–2100) percent departure from baseline (1970–2010) median precipitation under RCP 4.5 and RCP 8.5. Figure Credit: John Bradford, USGS Southwest Biological Science Center.

Escalante River flooding in 2010, which may become more frequent with climate change. Image Credit: NPS.

Reconstructions of past environments may help future scenario planning. For example, scientists have used tree ring data to reconstruct flows for the Colorado River over the last 1200 years (Lukas and Payton 2020). These data incorporate much more variability than are available in the observed stream gage records of the last ~100 years. Other paleo studies include plant remains found in ancient packrat (*Neotoma* spp.) middens. A 14,000-year-old packrat midden from Long Canyon suggests that plant species occurred 800–1,200 m (2,625–3,937 ft) lower in elevation than they do today (Spence and Cushing 2019). Similarly, some Douglas fir (*Pseudotsuga menziesii*) stands in GLCA occur about 300–500 m (984–1,640 ft) below the typical lower limit for this species (Spence 1995). Yet these pockets of Douglas fir appear healthy with recruitment of seedlings. These low-elevation pockets of Douglas fir may be relict species from the late Wisconsin or early Holocene (~11,000 years ago) (Spence 1995). Notably, the five stands studied in GLCA all occurred on north-facing alcoves near springs (Spence 1995). Cartwright et al. (2020) posits that springs may function as climate refugia for some species. This is particularly true for many of the endemic plant species still occurring in and around the hanging garden seeps and springs scattered throughout GLCA in the deep canyons and alcoves.

Current CO_2 levels are higher than they have been for the last three million years (Tierney et al. 2020). The middle Pliocene (~4 million years ago) is a potential future climate analog for Earth—a time when southern beech (*Nothofagus* spp.) grew in Antarctica (Thompson and Fleming 1996). Even under an aggressive climate amelioration scenario, CO_2 concentrations will remain at Pliocene-like levels until 2350 (Tierney et al. 2020). Under a middle of the road scenario, Pliocene-like CO_2 levels may persist for another 30,000 years. Although there have been abrupt changes in climate in the past, the current rise in temperature has occurred in only the last 150 years, which is 10–15 times faster than during the Pleistocene-Holocene transition (Butterfield et al. 2019; Tierney et al. 2020). The current rate of climate change necessitates an integration of climate considerations into all park activities, implementation of adaptive strategies that promote ecosystem resilience and enhance restoration, and prioritization of management strategies, among other actions. The NPS's climate change response strategy moves "beyond the question of whether the Earth is warming and is focused on what to do about it" (NPS 2010).

Large expanses of lake bed sediments near Hite, Utah with Russian thistle in the middle. Image Credit: NPS.

2.8. Upland Watershed Activities

The conditions of the upland watersheds greatly influence the health of GLCA's water-dependent systems and the natural resources that depend on those systems, which is reflected in the manager questions and information needs identified during GLCA's NRCA study (Appendix A). Using the Conservation Biology Institute's 2015 model of aquatic intactness for subwatersheds across the Colorado Plateau, an estimate of condition "based on the extent to which human impacts such as water demand, agriculture, urban development, natural resource extraction, dams, diversions, and alterations have disrupted the hydrology, water quality, and habitat quality of aquatic systems" (Bryce et al. 2012) was reported as an indicator of condition in Chapter 3's riparian zone condition assessment. Aquatic intactness scores across all subwatersheds occurring entirely or partially within GLCA were summarized, but the primary focus included the watersheds that overlapped the subset of streams evaluated for current conditions. Please refer to section 3.4 for additional information.

Chapter 3. Focal Resource Evaluations

Chapter 3 reports on the conditions or states of GLCA's selected focal natural resources. We evaluate these resources as either a condition assessment or gap analysis, depending on data availability (Figure 3-1).

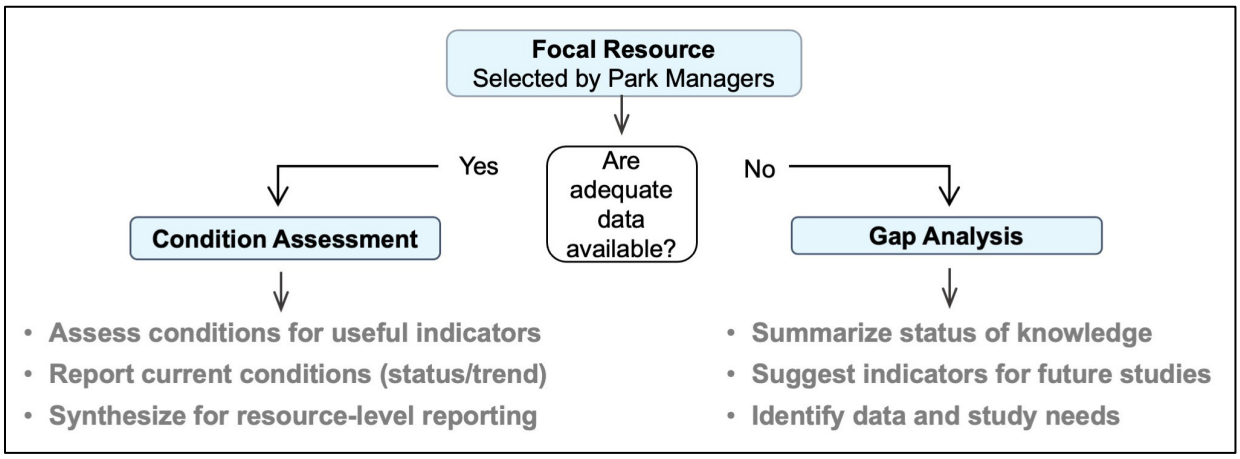


Figure 3-1. Two levels of evaluations are reported in NRCA studies depending on data availability: condition assessment and gap analysis.

For focal resources that lack adequate data for credible evaluations of their current conditions, we develop a gap analysis. A literature review, combined with expert input, produces a management-useful summary of the focal resource: its ecological importance, the general status of knowledge regarding factors influencing conditions, and useful data, indicators, and studies to consider in the future for improving managers' understanding of the resource.

For focal resources that have adequate data to assess current conditions for one or more indicators of condition, we develop a condition assessment. For each indicator, data for one or more measures are evaluated either qualitatively and/or quantitatively and combined to report a condition rating at the indicator level. Rating statements include the combined measures' qualitative characteristics, and when available, quantitative values, for a range of good to poor conditions for each indicator (see Figure 3-2 for rating classes and colors). Sometimes, the indicator of condition is unknown and shown in gray. The rating statements need to include logical and defensible criteria for assigning a condition level. We do not report a condition rating for the focal resource itself because of the complexity of characterizing condition at that level adequately.

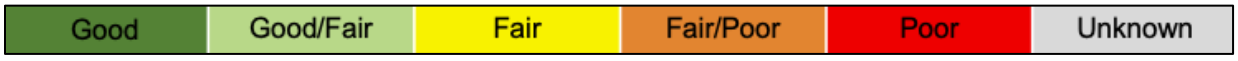


Figure 3-2. Indicators of condition rating classes and colors.

Each condition rating is assigned a confidence level, which is reported as high, medium, or low, depending on factors such as repeatability, age of data, and whether data were collected or modeled. A condition rating trend is reported as improving, stable, deteriorating, or unknown.

GLCA's natural resource condition evaluation findings were reported for eight, Hydrologic Unit Code (HUC8) watersheds when possible. GLCA occupies the lower portions of the Lower Lake Powell, Upper Lake Powell, Lower San Juan, Escalante, Lower Green, Lower Colorado-Marble Canyon, Paria, and Dirty Devil watersheds, listed in order of largest area to smallest, respectively (Table 3-1), with five of the watersheds comprising 96.3% of GLCA's total area (Figure 3-3). A summary of the focal resources and associated watershed where reported is shown in Figure 3-4.

Table 3-1. HUC8 watershed summary for GLCA.

Watershed (HUC8)	Area (km^2)	Proportion (%) of Watershed Occupied by GLCA	Proportion (%) of GLCA Area in Watershed
Lower Lake Powell	7,600	15.0	22.5
Upper Lake Powell	7,406	25.8	37.8
Lower San Juan River	6,315	6.7	8.4
Escalante	5,247	19.0	19.8
Lower Green	4,837	8.1	7.8
Lower Colorado-Marble Canyon	3,800	0.5	0.3
Paria	3,675	0.2	0.2
Dirty Devil	2,184	7.2	3.1

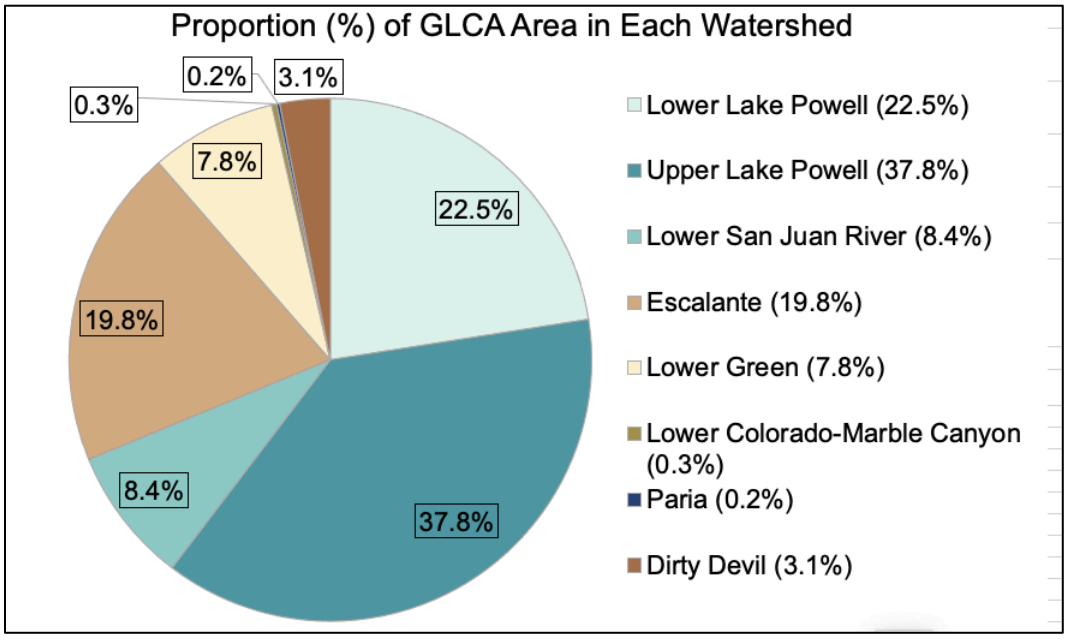


Figure 3-3. Proportion of GLCA's area in eight watersheds.

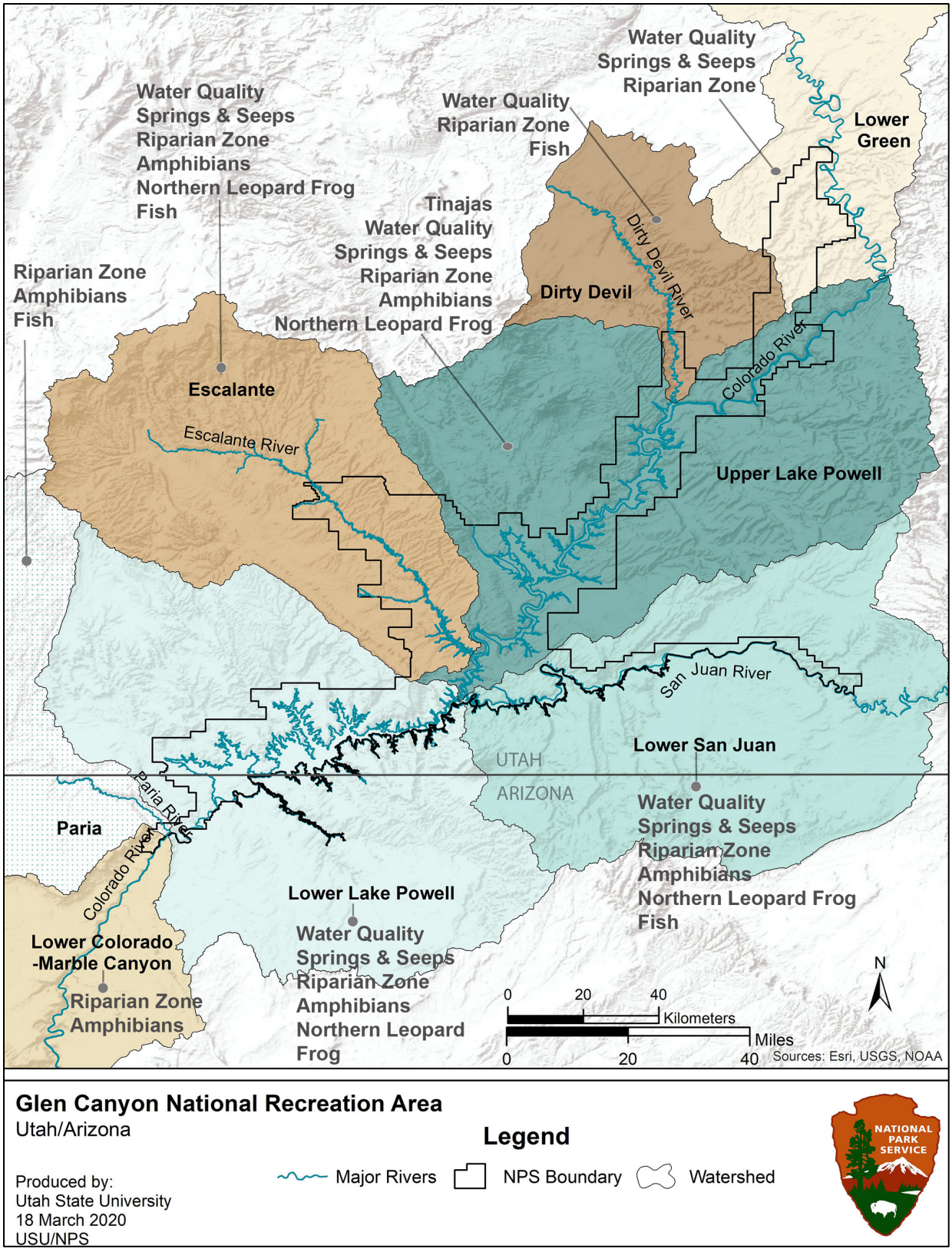


Figure 3-4. GLCA's selected focal resources were evaluated and reported within eight watersheds.

3.1. Tinajas (Gap Analysis)

3.1.1. Background & Importance

Tinajas (also referred to as waterpockets, ephemeral pools, potholes) are depressions eroded into sandstone bedrock by water, wind, and/or chemical weathering processes (Brown and Johnson 1983; Spence and Henderson 1993). Davis (2013) proposed that diatoms might also play a pivotal role in their development. Tinajas on the Colorado Plateau tend to occur in incipient ephemeral channels (Spence and Henderson 1993) and are filled entirely by precipitation and snowmelt (Christiana 1991). While smaller tinajas may dry out, larger tinajas retain water for several months to year-round depending on size (Spence and Henderson 1993). Some of the larger, perennial tinajas support riparian plants (Heil et al. 1993; Spence and Henderson 1993; Spence 1996a). Regardless of permanence, all tinajas serve as important sources of water for GLCA's amphibians, aquatic invertebrates, and mammals (Spence and Henderson 1993; Baron et al. 1998). They also hold water that may seep into the sandstone or flow through cracks downslope to other seeps and springs (GLCA, K. Hyde, NPS Chief of Science and Resource Management, review, 19 April 2021), but recharge zones for GLCA's groundwater-dependent resources are not understood and represent a knowledge gap. Not only are tinajas important for plants and wildlife, they are also culturally significant landscape features. Historically, Indigenous communities relied on permanent pools when water was scarce elsewhere (Brown and Johnson 1983). Tinajas continue to serve as an important source of water for backcountry users today (Brown and Johnson 1983).

A tinaja with vegetation is located in the lower right corner of the image. Note the lack of vegetation throughout the area underscoring the importance of tinajas as water sources. Image Credit: NPS.

3.1.2. Status of Knowledge

Tinajas represent the most numerous and widespread source of surface water in GLCA (Wood and Kimball 1987). Despite their abundance and importance, only one survey of flora at three tinajas in the recreation area has occurred (Spence 1996a). The three tinajas were located west of lower Hall's Creek in the Waterpocket Fold. Narrowleaf willow (*Salix exigua*), white sagebrush (*Artemisia ludoviciana*), Heller's rosette grass (*Dichanthelium oligosanthes*), little bluestem (*Schizachyrium scoparium*), and poverty rush (*Juncus tenuis*) were the most prevalent species (Spence 1996a). Although no biogeographically restricted or Colorado Plateau endemic species were reported for the three tinajas surveyed, these tinajas were floristically distinct from riparian vegetation plots and tinajas farther north in CARE (Spence 1996a; Spence and Henderson 1993).

The only other known study for GLCA is a survey of the physical characteristics of giant weathering pits in Cookie Jar Butte (Nethoff et al. 1995). Although giant weathering pits are similar to tinajas, they are formed by different erosional processes with a more significant wind component (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, comments on an earlier draft, 19 November 2020), and do not occur in drainages like many tinajas (Davis 2013).

The weathering pits at Cookie Jar Butte may be some of the deepest weathering pits in the world (Nethoff et al. 1995); they can be as wide as 38 m (125 ft) and as deep as 17 m (56 ft). Four types of weathering pits are found at Cookie Jar Butte, including shallow, pan pools; deep, steep-sided cylindrical pools; sloped pools shaped like an armchair; and bowl-shaped pools (Nethoff et al. 1995). Weathering pits at Cookie Jar Butte are eroded into Entrada sandstone, but this landscape feature is also common in Navajo Sandstone and the Carmel Formation (Graham 2016). Weathering pits are also found at the north end of Rock Creek Bay and Warm Creek Bay (Graham 2016), while smaller tinajas are located in the Waterpocket Fold (Berghoff 1995).

Using ArcMap 10.4, we identified areas in GLCA that are likely to contain tinajas based on the NPS geology (Graham 2016) and the NPS vegetation mapping geodatabases (Tendick et al. 2017). The geology data included only Entrada Sandstone, Navajo Sandstone, and the Carmel Formation. The two slickrock classes identified by Tendick et al. (2017) in the vegetation geodatabase, bare sandstone/slickrock and slickrock sparse shrublands, were also included. Using the Intersect tool in ArcMap 10.4, an area of 806 km^2 (311 mi^2) resulted as the core area of potential tinaja occurrence (Figure 3.1.2-1). Nearly the entire area (97%) was located in three watersheds: Upper Lake Powell (52%), Escalante (26%), and Lower Lake Powell (19%).

Because of the large potential area for tinaja occurrence, further analysis was restricted to the Waterpocket Fold of GLCA (Figure 3.1.2-2). This resulted in an area of analysis (AOA) that was bounded by Hall's Creek to the east, the Colorado River to the south, the Upper Lake Powell–Escalante watershed boundary to the west, and the boundary between GLCA and CARE to the north. The AOA, entirely within the Upper Lake Powell Watershed, totaled 223 km^2 (86 mi^2) and is underlain by Navajo Sandstone (Figure 3.1.2-2).

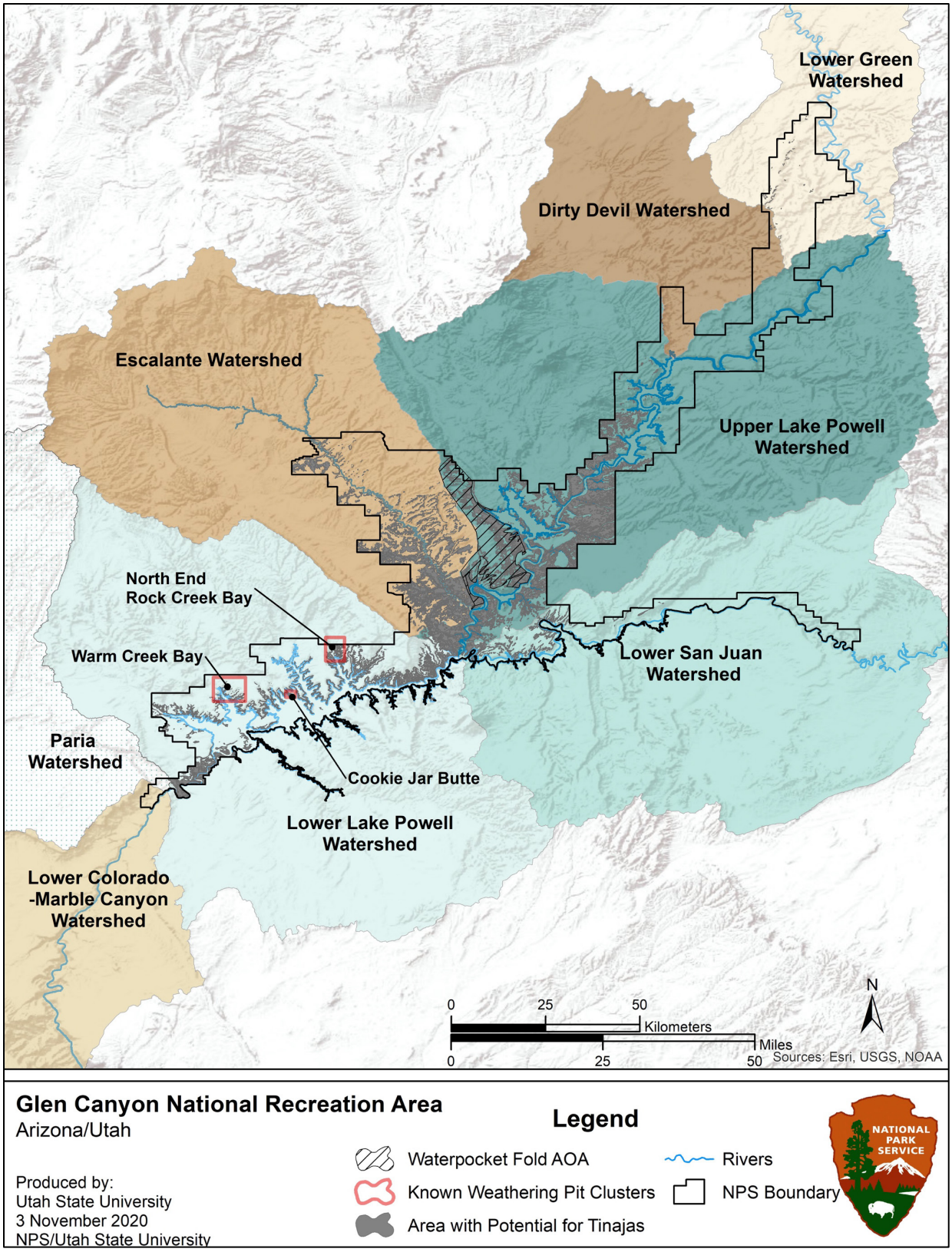


Figure 3.1.2-1. Potential area for supporting tinajas. The North end of Rock Creek Bay, Warm Creek Bay, and Cookie Jar Butte support giant weathering pits while tinajas are most common in Waterpocket Fold.

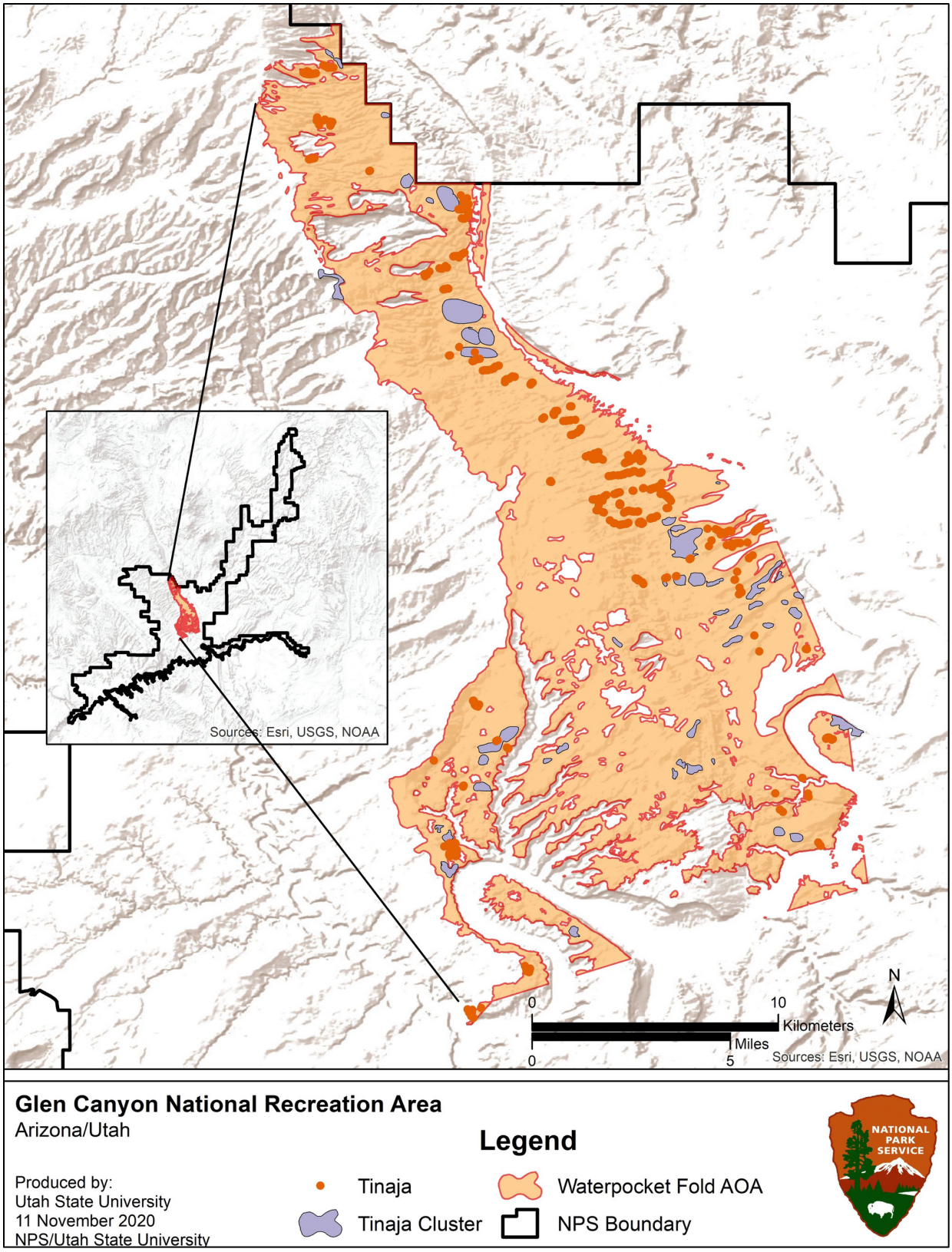
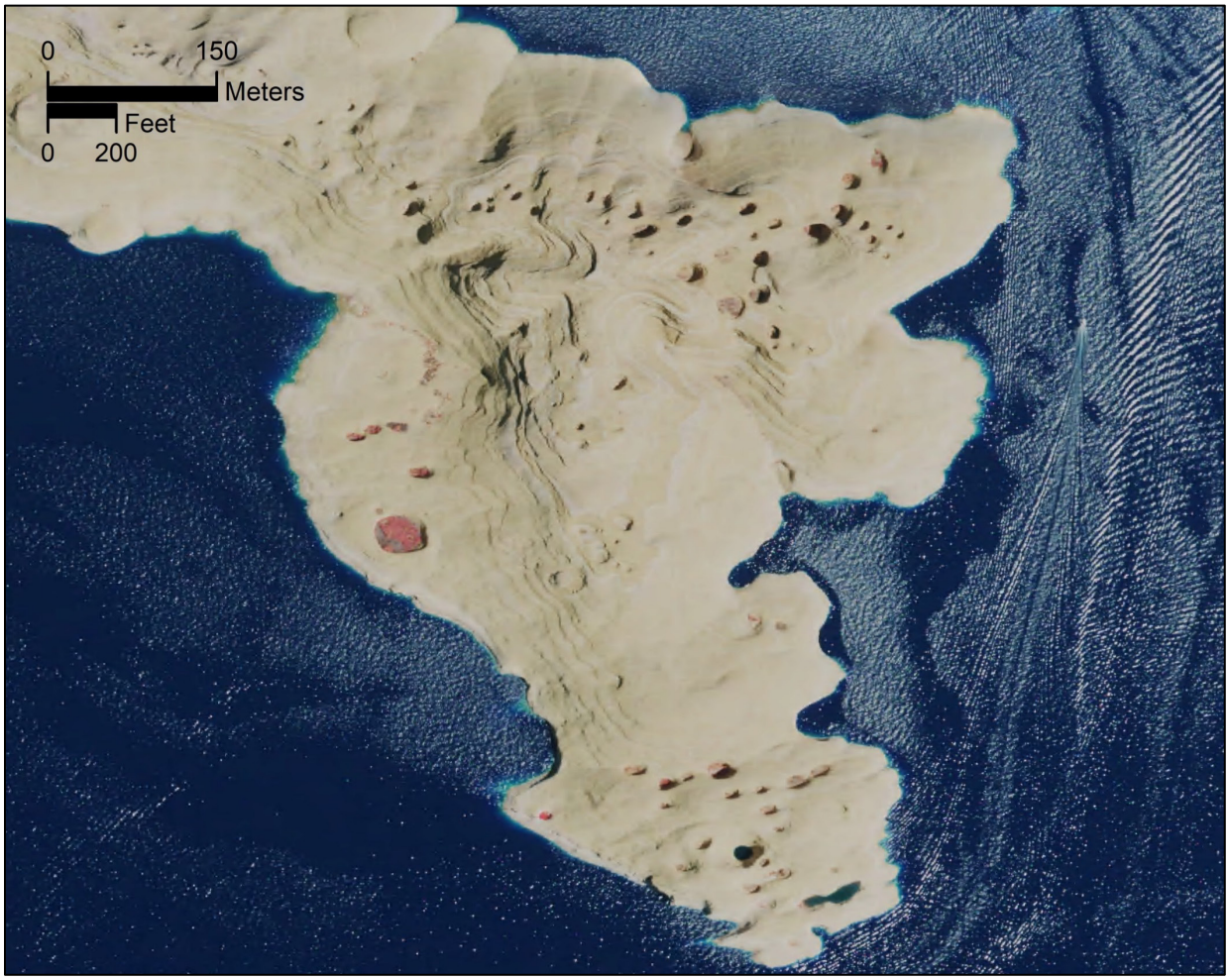


Figure 3.1.2-2. Tinajas mapped in Waterpocket Fold area of analysis.

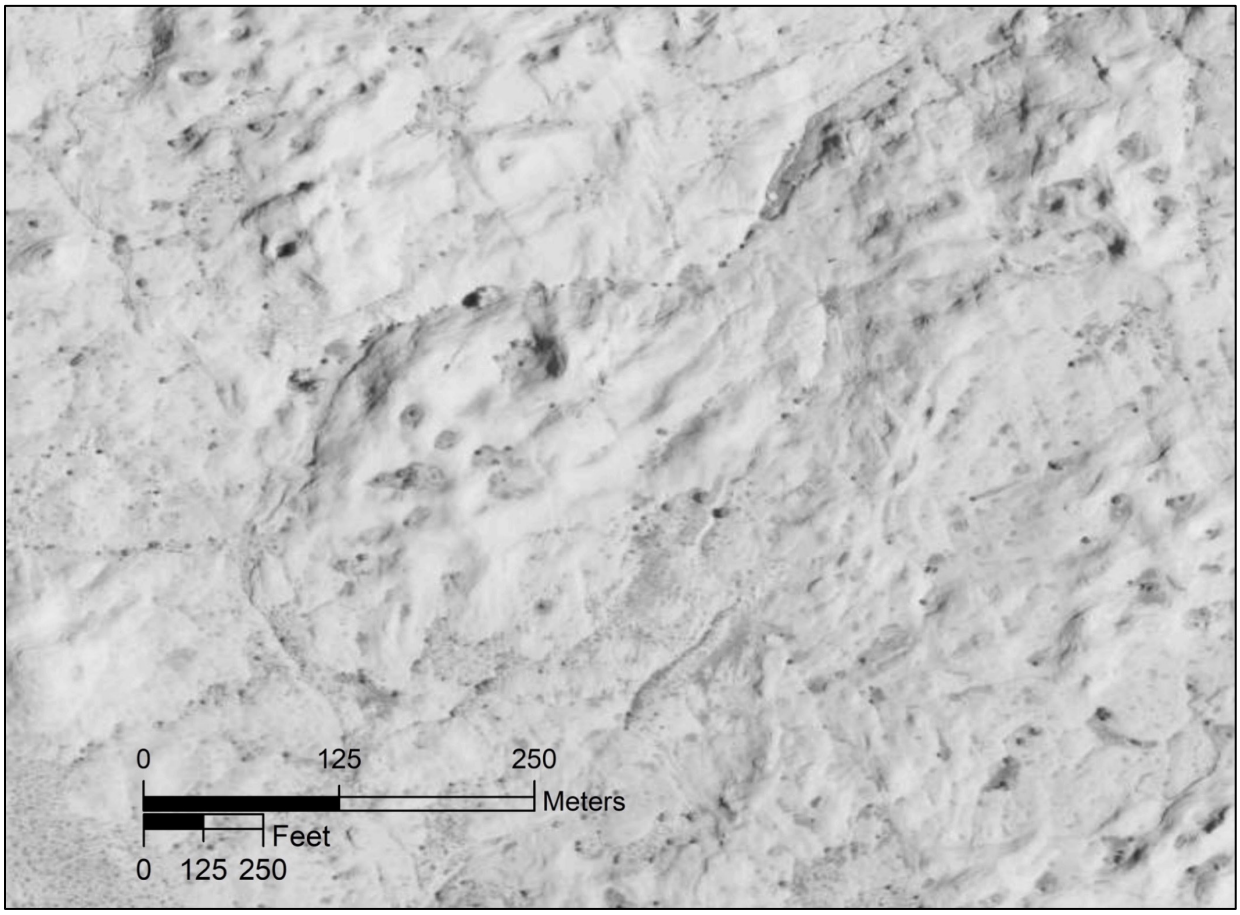
The Waterpocket Fold AOA was systematically searched, using a grid of polygons created using the Fishnet tool in ArcMap 10.4. Each polygon was searched for visible tinajas using 2016, 0.6-m (2.0-ft) near-infrared aerial photographs and 2018, 0.6-m (2.0-ft) natural color aerial photos, collected by the U.S. Department of Agriculture's (USDA) National Agriculture Imagery Program (NAIP) (USDA 2020a). Two sets of aerial images were used because of the high variability in feature shape, depth, presence of water, and occurrence of vegetation. Tinajas were most apparent using near infrared aerial photos, but the natural color photos helped to differentiate between shadows created by rock walls and tinajas with water and plants. Individual tinajas were mapped when they occurred singly or in small groups, but for larger clusters (>10), a polygon was drawn around the majority of features. A total of 588 individual tinajas and 47 tinaja clusters in the Waterpocket Fold AOA were identified (Figure 3.1.2-2). Most features occurred on the east side of the fold in large clusters that appeared to be shallow with some vegetation.



Aerial image of weathering pits in Cookie Jar Butte. Image Credit: USDA (2020a).

Tinajas in the Waterpocket Fold AOA were significantly smaller than the weathering pits in Cookie Jar Butte and were therefore more challenging to map. In CARE, Coles et al. (2009) write that many

tinajas are “too small to distinguish on aerial imagery.” Tinajas may be more apparent in imagery collected between December and March because they tend to be full of water during this cooler, wetter period of the year, and are in high contrast with the surrounding slickrock, reflecting morning and evening low-angle sun (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, comments on study details table, 19 November 2020). Although tinajas were mapped in the Waterpocket Fold AOA, there are likely many more features that were not observable, especially those in shadow or in drainages.



Aerial image showing a cluster of tinajas in Waterpocket Fold. Image Credit: USDA (2020a).

Although there is only one basic survey of tinajas in GLCA, there have been several studies of tinajas in CARE during the 1990s, which include the north end of Waterpocket Fold (Baron et al. 1998; Berghoff 1995; Haefner and Lindahl 1991; Spence and Henderson 1993). There are also a few studies of tinajas elsewhere on the Colorado Plateau (Chan et al. 2005; Davis 2013; Gladney et al. 1993), but since CARE borders GLCA, studies conducted there to describe the physical characteristics of tinajas, as well as the potential plants, invertebrates, and amphibians that may also occur in GLCA’s Waterpocket Fold tinajas are included in this gap analysis.

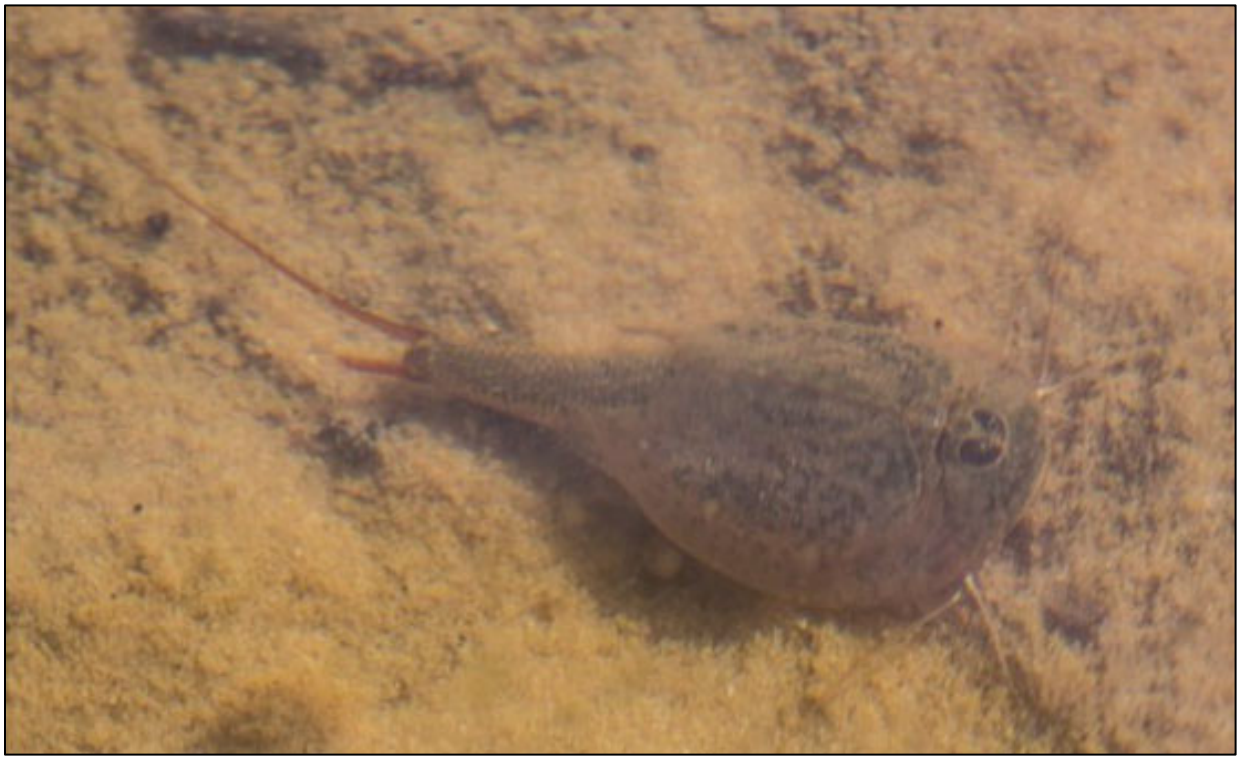
Based on Baron et al. (1998), in CARE’s Waterpocket Fold, tinaja pool volume may range from a few liters to >1,000 m^3 (35,315 ft^3), with sediment depths up to 2.0 m (6.5 ft). Pools with greater than

90 m^3 (3,178 ft^3) are usually perennial unless they are shallow (0.4 m [1.3 ft]) or there is a prolonged drought (Haefner and Lindahl 1991). A study of 463 pools at CARE found that pool water volume ranged from 0 m^3 to 1,532 m^3 (54,102 ft^3), with a mean volume of 21 m^3 (742 ft^3), but most pools were ≤15 m^3 (530 ft^3) (Baron et al. 1998). This suggests that most pools are ephemeral. The amount of water collected in perennial pools and the length of time ephemeral pools retain water depends on the amount and frequency of precipitation and rates of evaporation. The degree of shading also influences how long tinajas remain filled. In CARE, most tinajas were shaded for at least part of the day; only 26% of tinajas were entirely exposed to sun throughout the day (Berghoff 1995).

Cattle at waterpockets. Image Credit: NPS.

Vegetation was a key indicator of water permanence for tinajas in CARE (Berghoff 1995). Even if water appeared absent in a pool, the presence of vegetation indicated the presences of subsurface water. Pools with vegetation lost water faster than pools without vegetation due to evapotranspiration, but vegetation also provided shade (Berghoff 1995). At tinajas where plants occurred, diversity was high, particularly at deep pools shaded by rock (Spence and Henderson 1993). In some cases, tinaja plant diversity can be higher than in smaller hanging gardens; however, the larger hanging gardens are known as biodiversity hotspots (Spence and Henderson 1993).

Berghoff (1995) found 91 species across the 463 tinajas surveyed in CARE, and more than half (65%) of all tinajas included plants. Most species were riparian obligates with at least one obligate species occurring in 25% of all tinajas sampled. Emergent vegetation growing in or very near the edge of the water included common reed (*Phragmites australis*) and bulrush (*Typha latifolia*), but these two species never occurred at the same tinajas. Woody riparian species included cottonwood (*Populus fremonti*), Goodding's willow (*Salix gooddingii*), non-native saltcedar (*Tamarix ramosissima*), sandbar willow (*Salix exigua*), and Box elder (*Acer negundo*). Spence and Henderson (1993) found that the most widespread wetland species at tinajas included, non-native creeping bentgrass (*Agrostis stolonifera*), western aster (*Symphyotrichum chilensis*), arctic rush (*Juncus arcticus*), scratchgrass (*Muhlenbergia asperifolia*), Hooker's evening primrose (*Oenothera elata*), rosette grass (*Panicum oligosanthes*), Goodding's willow, and western goldentop (*Solidago occidentalis*). The most common non-wetland species included white sagebrush (*Artemisia ludoviciana*), non-native cheatgrass (*Bromus tectorum*), paintbrush (*Castilleja linariifolia*), goldenaster (*Heterotheca villosa*), and wooly plantain (*Plantago patagonica*). Spence and Henderson (1993) reported 88 species at 28 sites (22 tinajas and 6 hanging gardens). Overall, tinajas were uniform in species composition, especially with respect to obligate riparian plants and were floristically distinct from hanging gardens. However, no endemic plant species were found at tinajas.



Tadpole shrimp is one of many species specialized for a short life cycle in temporary pools of water, such as tinajas. Image Credit: NPS/Jacob Frank.

Few vertebrate species occurred in CARE's tinajas. They were fathead minnow (*Pimephales promelas*) and five species of amphibian (Baron et al. 1998; Berghoff 1995). The amphibians were

Great Basin spadefoot (*Spea intermontana*), Woodhouse's toad (*Anaxyrus woodhousii*), canyon treefrog (*Hyla arenicolor*), red-spotted toad (*Anaxyrus punctatus*), and northern leopard frog (*Lithobates pipiens*), which are all native except for the fathead minnow (NPSpecies 2020).

In general, tinajas are best known for the micro- and macroinvertebrate communities they support. Baron et al. (1998) documented 52 macroinvertebrate species. Fairy shrimp (*Streptocephalus texanus*) occurred in all 20 pools sampled and the pond snail (*Physella* spp.) occurred in each of the five drainages sampled. Haefner and Lindahl (1991) also reported pond snails. The other 50 species were arthropods, which included flies (Order Diptera), beetles (Order Coleoptera), true bugs (Order Hemiptera), and dragonflies and damselflies (Order Odonata) (Baron et al. 1998). Nearly all species are common to other waterbodies of the Colorado Plateau. Although pools with plants supported a greater number of invertebrates, no species were restricted to pools with plants (Baron et al. 1998). Both Berghoff (1995) and Haefner and Lindahl (1991) found similar results.

Copepods (*Eucyclops agilis*), cladocerans (*Daphnia similis*, *Ceriodaphnia quadrangular*), six species of rotifer (also known as water bears), and other drought resistant invertebrates are common in tinajas (Haefner and Lindahl 1991). Because tinajas are prone to environmental extremes, invertebrate community composition often remains stable before and after disturbances like flooding and drying (Baron et al. 1998). Many species are also adapted for rapid recolonization following disturbances. Organisms may tolerate desiccation for long periods of time (i.e., cryptobiosis); they may seal moisture inside their bodies, becoming resistant to desiccation; or they may simply disperse to other pools (Chan et al. 2005). Some organisms found in desert pools can tolerate conditions that they have not experienced in their evolutionary history. For example, brine shrimp (*Artemia* spp.) eggs were affixed to spacecraft and then successfully hatched upon returning to Earth and rotifers have survived exposure to extreme temperatures (Chan et al. 2005).

3.1.3. Discussion

Currently, no parks are managing tinajas, though several parks are monitoring them. Their largely ephemeral nature makes them a challenge to study; however, McIntyre et al. (2018) developed a protocol for monitoring springs, seeps, and tinajas in Sonoran and Chihuahua Desert parks, including Saguaro NP and Organ Pipe Cactus NM where tinajas are particularly abundant. McIntyre et al. (2018) include water quality, water quantity, vegetation, and disturbance as monitoring objectives. Based on McIntyre et al. (2018), Borthwick (1993), and Berghoff (1995), a set of potential indicators and measures for studying tinajas at GLCA in the future are presented in Table 3.1.3-1.

In addition to water quality, plants, and disturbance, biological surveys of vertebrates and invertebrates should also be included in future monitoring efforts. Because the amount of water in tinajas varies both spatially and temporally, biodiversity surveys may serve as a proxy for determining the proportion of pools that are perennial. For example, the presence of riparian obligate plants is a good indicator of perennial water, but pools may appear dry even with riparian plants due to soil water saturation. Additionally, dragonfly larvae and nymphs are not usually found in ephemeral pools because of the limited time available to grow and emerge as adults (Jocque et al. 2010). Therefore, the presence (or absence) of certain species may indicate how long pools retain water.

Table 3.1.3-1. Proposed study details for tinajas.

Potential Indicator	Potential Measure	Potential Reference Criteria for Measure
Water Quantity	Number of Wet and Dry Days (temperature sensors can serve as a proxy)	Because rain-fed tinajas are mostly ephemeral and few reports included water persistence through time, there is no readily available reference criterion.
	Precipitation Amount and Frequency	Natural, historical patterns of precipitation persist, though there may be high annual variability.
Water Quality	Core Water Quality (pH, temperature, dissolved oxygen, conductivity)	Within the range considered typical for tinajas.
	Chemistry (major ions, mercury, and other contaminants)	Within the range considered typical for tinajas.
Community Composition	Non-native Invasive/Non-native Species Richness	Non-native species are absent.
	Native Beta and Alpha Richness (invertebrates, plants, amphibians)	Species representative of taxa commonly found in undisturbed tinajas with species at some pools indicating permanent water.
Disturbance	Categorical Rating of Anthropogenic Disturbance	Undisturbed

Precipitation may also serve as a proxy for pool saturation. Because of high variability in precipitation from one drainage to another, in situ rain gauges placed in a cluster of tinajas would increase the accuracy of using precipitation as a proxy (Baron et al. 1998). Temperature gauges placed directly in a pool can also serve as a proxy for water presence/absence (Raymond et al. 2019). Water quality in tinajas is affected by precipitation, time since precipitation, bedrock substrate, and disturbances. Because tinajas are unique systems, state water quality standards may not apply. For example, it is typical for small, shallow pools to become hypoxic or anoxic (Raymond et al. 2019). Data provided in Baron et al. (1998), Berghoff (1995), Gladney et al. (1993), and Haefner and Lindhal (1991) may provide baseline information for water quality.

Climate change is the primary driver affecting tinajas in GLCA, with a severe drought occurring in the region from about 1999 to 2005 (Spence and Cushing 2019) and extreme to exceptional drought conditions occurring at the time of this document's publication (National Drought Mitigation Center 2021). Approximately 30–35% of annual precipitation in GLCA occurs during the summer monsoon season (Spence 2001; Spence and Cushing 2019); however, in both 2019 and 2020, little to no precipitation occurred during the typical monsoonal period (GLCA, K. Hyde, NPS Chief of Science and Resource Management, review, 19 April 2021). Temperature, precipitation, and rates of evapotranspiration vary substantially in different areas of the park (Spence and Cushing 2019). Overall patterns, however, show increasing temperatures of ~1 °C (1.5–2.0 °F), but no trends in precipitation (Spence and Cushing 2019).

Climate change (warmer and drier conditions) will affect the amount and persistence of water in tinajas since they are supplied solely by precipitation and runoff. If tinajas throughout GLCA are similar to tinajas in CARE, then it's likely that the vast majority of species that occur in tinajas are

widespread on the Colorado Plateau. None of the studies included in this gap analysis found endemic species in tinajas, so it seems reasonable to not expect loss of endemic species with changing climate if the species assemblages are similar between areas of the Waterpocket Fold in CARE and GLCA. However, the more frequent or longer-term drying of tinajas that may serve as upslope water sources for springs could contribute as a stressor to the endemic plants found within the springs (GLCA, K. Hyde, NPS Chief of Science and Resource Management, review, 19 April 2021).

In addition to climate change, anthropogenic disturbance is also a driver and stressor of tinaja health. In 2013, Organ Pipe Cactus NM identified human impacts to tinajas, which affected water quality and probably the utilization of this resource by wildlife (NPS 2013). Although rain-fed tinajas are resilient to extremes in temperature, flooding, and drought, current human disturbances may alter community structure, introduce non-natives species, and affect water quality. Managers identified increased visitor use as an emerging concern for this resource, including contamination from personal care products (e.g., sunscreen) and *Escherichia coli* (*E. coli*).

3.2. Water Quality of Springs & Seeps (Gap Analysis)

3.2.1. Background & Importance

The interaction of local geology, hydrology, and regional watershed characteristics influence attributes of water quality at spring ecosystems (Springer et al. 2006; Taylor et al. 1997, 2004). Water quality is also highly sensitive to natural and human disturbances such as erosion, agricultural runoff, cattle grazing, toxins, recreational use, and atmospheric deposition (Sather et al. 2013; Weissinger et al. 2012). Many studies have documented that some springs and seeps transport wastewater, pharmaceuticals, coal combustion products, and petroleum-related compounds, in addition to other pollutants to surface waters (O'Driscoll et al. 2019). Although baseline water quality data exist for some springs in GLCA (Taylor et al. 2004), more data are needed to assess the condition of this resource over time, across watersheds, and by spring type, especially given the importance of springs and seeps to birds, mammals, aquatic invertebrates, amphibians, and plants (Cartwright et al. 2020; Weissinger et al. 2012).

3.2.2. Status of Knowledge

There have been a number of studies on water quality for springs and seeps in GLCA (Figure 3.2.2-1). The first was conducted by Cooley (1965), who documented 363 springs in the Lake Powell area, many of which were inundated after the Glen Canyon Dam was constructed.

Citizen scientists identifying dragonflies, which may serve as indicators of water quality, including the presence of mercury. Image Credit: NPS Air Resources Division, Dragonfly Mercury Project.

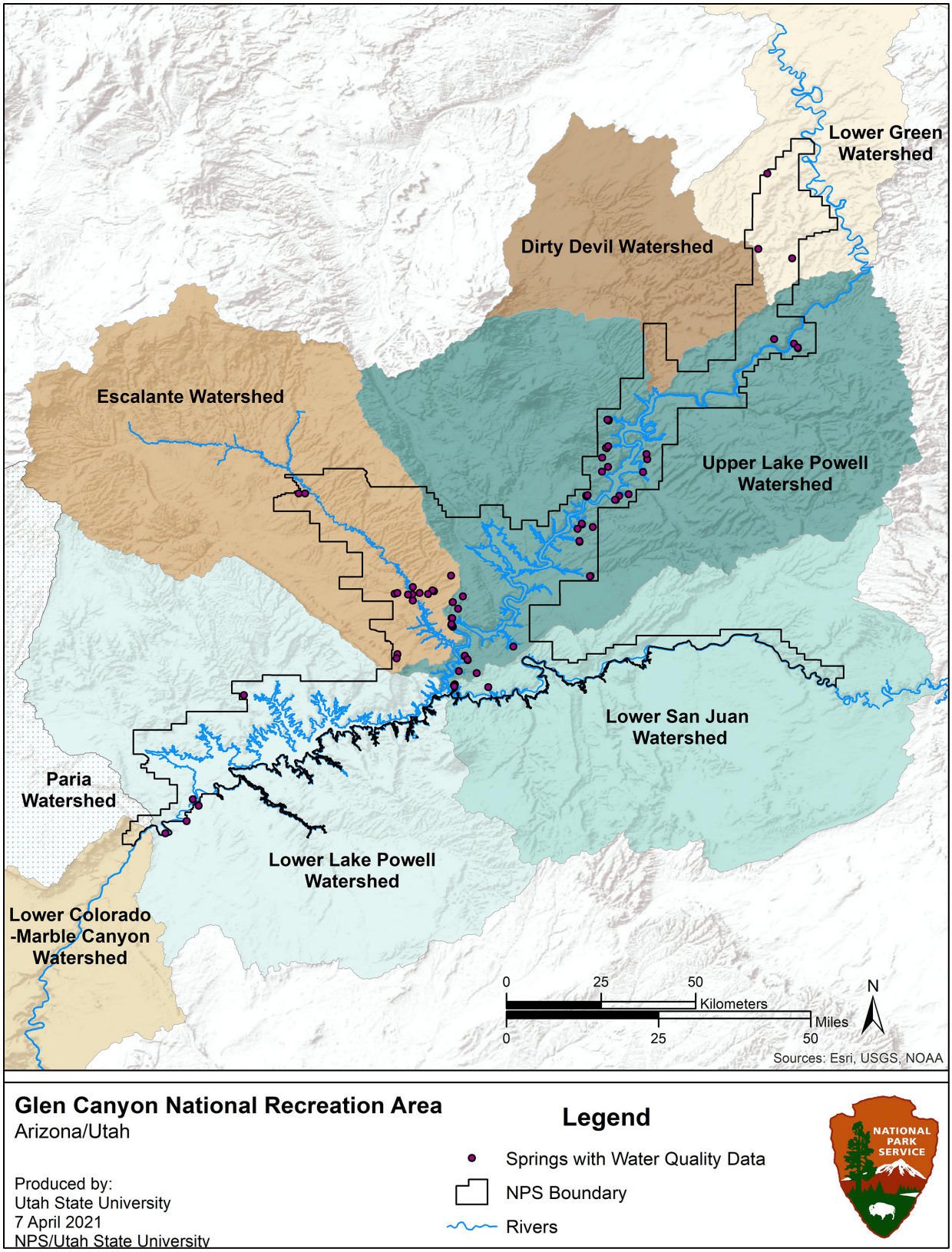


Figure 3.2.2-1. Locations of springs with water quality data. Note that location data were not available for 30 of the 109 springs.

The study's purpose was to survey springs before the creation of Lake Powell (Cooley 1965). In 1978, Hand (1979 as cited in Huntoon 1979) sampled 26 springs in and around the northern area of the park, primarily in the Hans Flat vicinity in the Lower Green Watershed. Neither Cooley (1965) nor Huntoon (1979) published location information for the springs sampled, though there may be coarse scale maps in Hand (1979), but the original thesis was not available. Williamson (1985) reported water quality data for 13 springs and seeps in Bowns Canyon (Upper Lake Powell Watershed), Wilson Mesa (Lower San Juan Watershed), and Orange Cliffs (Lower Green Watershed), but did not publish maps or location information for individual springs. In 1995, Taylor et al. (1997) surveyed 33 springs and seeps in GLCA primarily in the Upper Lake Powell and Escalante watersheds. In 1997 and 1998, Taylor et al. (2004) collected water quality data at some of the same springs and seeps surveyed in Taylor et al. (1997), but also included new locations for a total of 28 springs. And in 2005, Springer et al. (2006) collected water quality data at six springs in GLCA, which were located in the Escalante, Upper Lake Powell, and Lower San Juan watersheds. Lastly, Taylor et al. (1997, 2004) reported water quality data for 23 springs in multiple watersheds. These data were collected in 1997–1998.

In summary, water quality data were available for 109 springs in six of the park's eight watersheds; no springs were sampled in the Paria or Lower Colorado-Marble Canyon watersheds (Figure 3.2.2-1). However, not all water quality measures of interest (e.g., discharge, temperature, pH, heavy metals) were collected at each spring. Some springs were surveyed more than once for some water quality variables, but no spring was surveyed more than three times; however, assessing which springs were visited more than once was complicated by the fact that springs were referred to differently in the various reports and datasets and location information was not published in several reports. From site names, though, it appeared that none of the sites were consistently monitored.

A total of 125 discharge measurements were collected at 95 springs (Hand 1979 as cited in Huntoon 1979; Springer et al. 2006; Taylor et al. 1997, 2004; Williamson 1985). Most springs were sampled once, but 25 springs were sampled two or three times. As expected, discharge varied dramatically from a minimum of 0.0 mL/s to a maximum of 42,000 mL/s. Because of the high degree of variability, it was difficult to generalize about discharge, but some patterns emerged from the data. All but one discharge measurement was collected between May and September. Discharge in May was far greater than discharge in any other month (Figure 3.2.2-2). Discharge is related to spring type, but sample sizes were not large enough to separate data by this factor (spring type was not reported for most springs with water quality data). Most springs (70%) fell within the second (10–100 mL/s) and third (100–1000 mL/s) discharge magnitude classes (Figure 3.2.2-3) described by Springer et al. (2006). Nearly 9% of discharge measurements were below the ability of instruments to measure (0.0 mL/s). Seeps with zero magnitude discharge are some of the most common spring types in Southern Colorado Plateau parks and indicate extremely low discharge rather than springs that have gone dry (Springer et al. 2006).

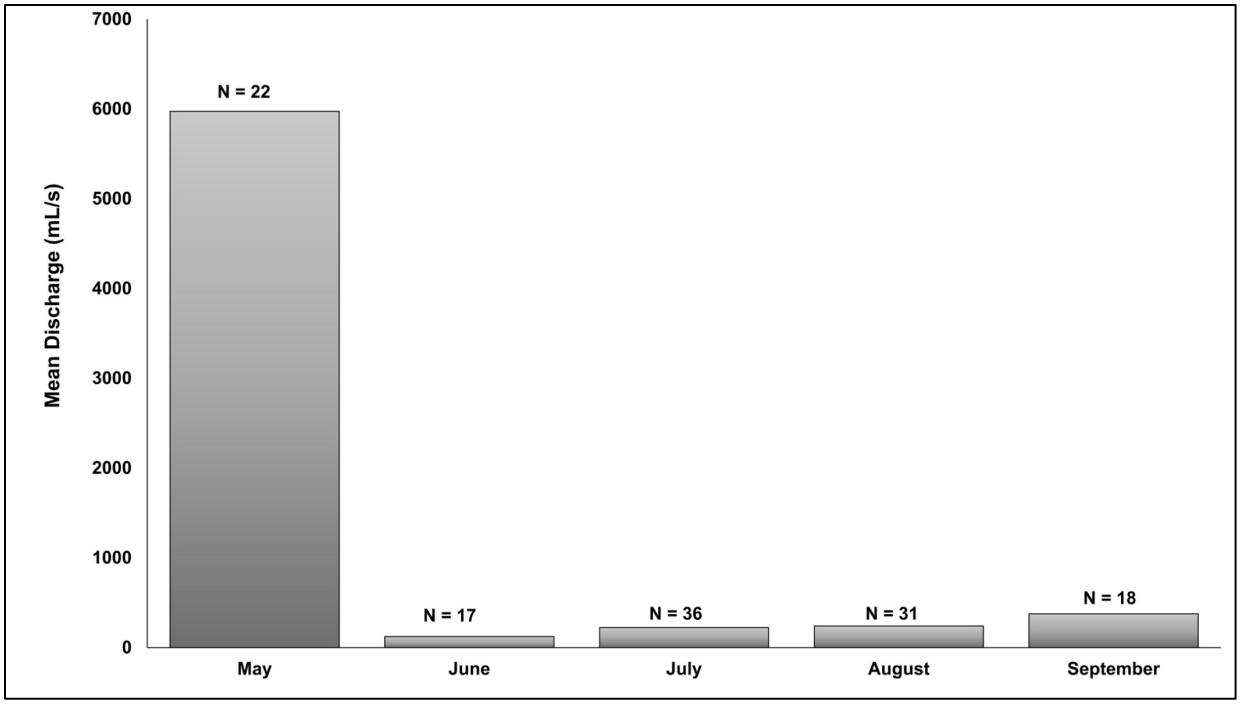


Figure 3.2.2-2. Mean spring discharge by month.

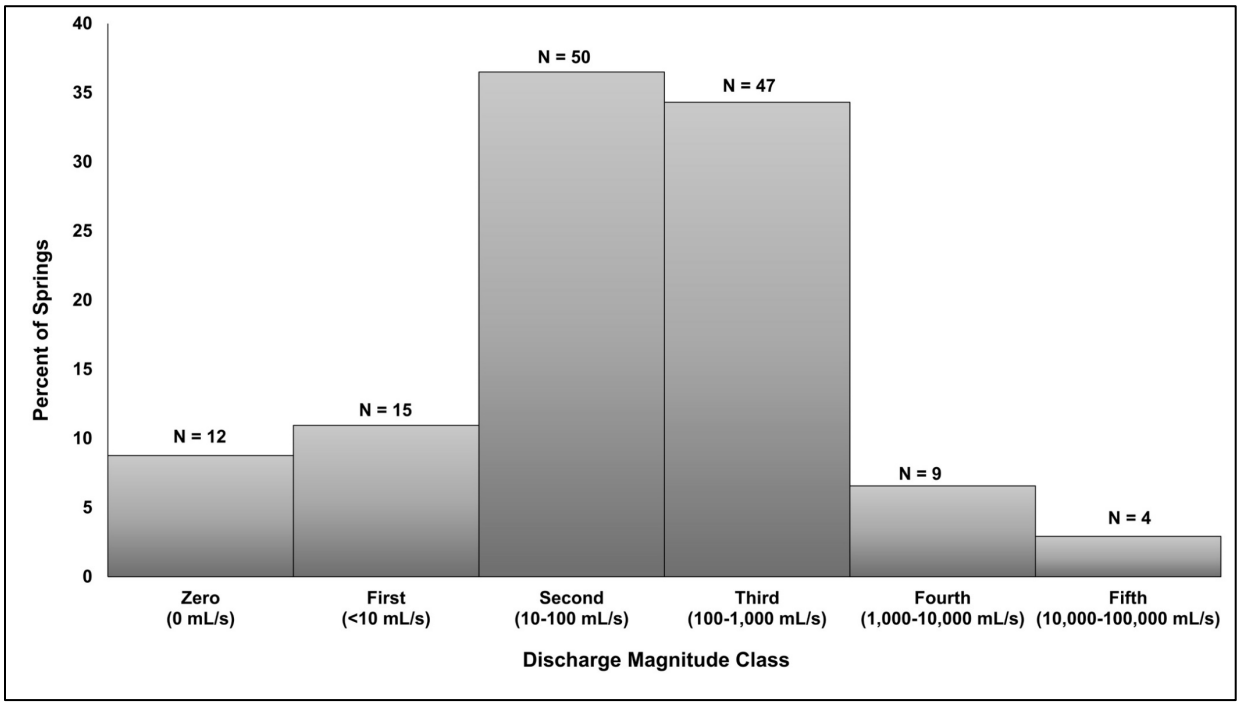


Figure 3.2.2-3. Percent of springs sampled in each discharge class. Classes are from Springer et al. (2006).

A total of 99 measurements at 90 springs were available for temperature, pH, specific conductivity and dissolved oxygen (Table 3.2.2-1) (Hand 1979 as cited in Huntoon 1979; Springer et al. 2006;

Taylor et al. 1997, 2004; Williamson 1985). In addition to reporting averages for all springs combined, we subset the data to compare core water quality measures for springs accessible to non-native ungulates to those that are not accessible (n = 12 for each variable and category except dissolved oxygen, which had 10 and 11 inaccessible and accessible springs). There were no significant differences in grazing accessibility for dissolved oxygen (t (10) = 1.53, p = 0.16), pH (t (13) = −0.14, p = 0.89), or temperature (t (19) = 0.75, p = 0.46). Specific conductance, however, was significantly greater in accessible sites than in inaccessible sites (t (13) = −2.43, p = 0.03).

Table 3.2.2-1. Core water quality data for springs & seeps by accessibility to grazing.

Measure	All Springs Mean (SD)	Not Accessible to Grazing Mean (SD)	Accessible to Grazing Mean (SD)
Temperature (°C)	19.95 (3.72)	22.16 (2.97)	20.97 (4.61)
pH (SU)	7.76 (0.62)	8.02 (0.63)	8.04 (0.20)
Dissolved Oxygen (mg/L)	6.58 (1.37)	6.91 (0.47)	5.90 (2.03)
Specific Conductance (µS/cm)	523.13 (1097.93)	201.50 (70.74)	407.67 (282.74)

Specific conductance is highly correlated to total dissolved solids, so this result is not surprising (Springer et al. 2006). For sites accessible to grazing, we expected higher specific conductance values because of erosion caused by ungulates. An alternative explanation is that some springs (e.g., Soda Spring) are naturally high in specific conductance (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, manager-scientist discussion, 14 January 2021). However, to determine the effects of non-native ungulates on water quality, a more robust sample size and regular monitoring program is needed.

Williamson (1985) reported that all measures of water quality, including trace metals, were well within expected ranges for groundwater. Although calcium and magnesium were higher than expected, Williamson (1985) speculated that this may have to do with long groundwater residence times. “Long residence times allow for extended chemical interaction between the water and the aquifer in which it is contained, resulting in greater concentrations of dissolve constituents” (Williamson 1985). Taylor et al. (1997, 2004) reported that trace compounds, including ammonium, nitrate, nitrite, and phosphate were measured at very low concentrations, and most constituents measured (e.g., cadmium, mercury, selenium, zinc) were not detectable with the instrumentation used (Taylor et al. 1997, 2004). These results indicate that when the data were collected, there appeared to be no contamination of groundwater sources.

GLCA natural resource management team collecting discharge and water quality data at a spring in Four Mile Canyon off of Lake Powell. Image Credit: NPS.

Aquatic invertebrate data were collected in 1997 and 1998 at 25 springs in GLCA ((NPS GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mailed park file to Lisa Baril, Utah State University, 18 December 2020); Taylor et al. 2004). In 2006, invertebrates were sampled at six springs in the park (Springer et al. 2006). Invertebrates were identified to the level of genus when possible in both studies (data collection methods are in Spence 2004). A total of 100 genera belonging to 11 orders were reported at the 25 springs sampled in 1997/1998 (Figure 3.2.2-4). Genus richness averaged 12.2 and order richness averaged 4.5 across the 25 springs. Of the 11 orders, Dipterans (true flies) were the most common, followed by Coleoptera (beetles). Richness of Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) (known as EPT) is often used as an indicator of water quality because species in these orders are generally intolerant of pollution (Brasher et al. 2011), but there were no Plecopterans, and Ephemoptera and Trichoptera richness were both somewhere in the middle of all richness values. However, Weissinger et al. (2012) point out that there are few data on tolerance values for macroinvertebrates in the American Southwest, and EPT taxa are underrepresented in Colorado Plateau springs. Indices of benthic macroinvertebrates have been widely applied to riparian systems to assess water quality, but to a much lesser extent in spring ecosystems (Weissinger et al. 2012). More research is needed to

determine the best macroinvertebrate indices for assessing water quality at springs on the Colorado Plateau.

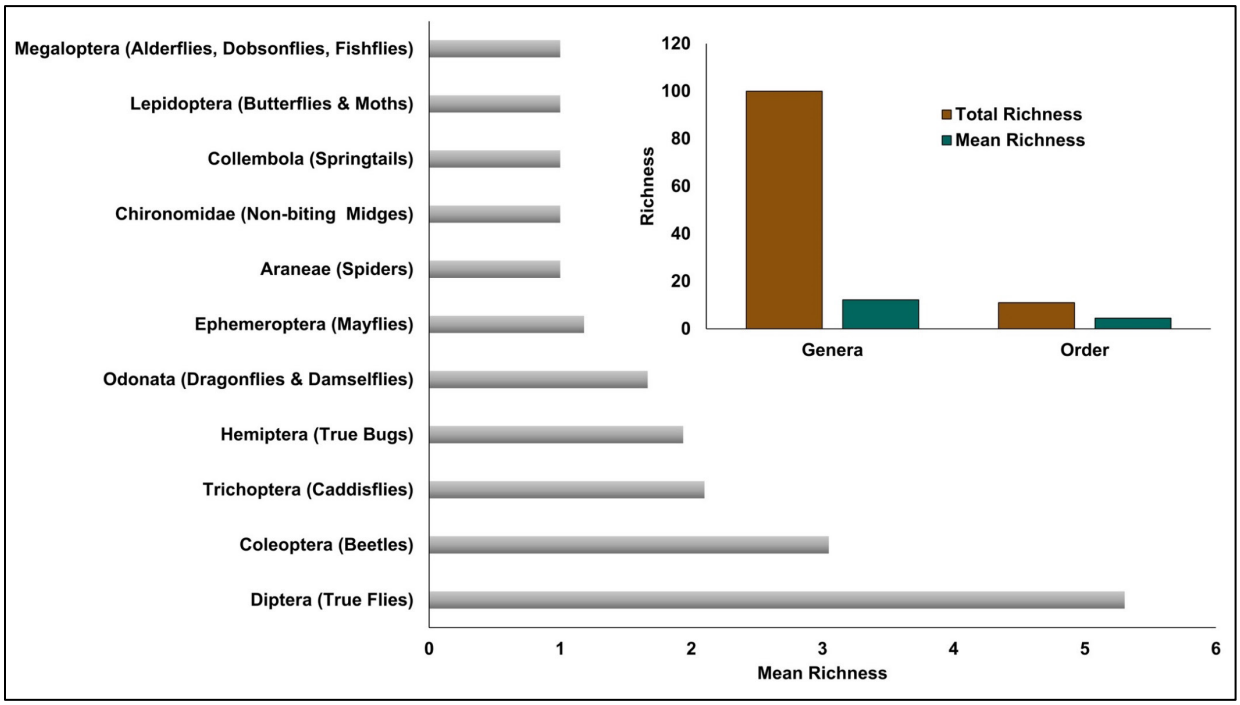


Figure 3.2.2-4. Mean invertebrate richness across taxonomic orders at springs (inset shows mean and total richness by genera and order).

In 2005, Springer et al. (2006) reported species in 16 orders. Although some specimens were identified to genus or species, most were not, so we restricted this summary to order only. Order richness averaged 6.0 across the six springs sampled. Amphipoda (crustacean), Decapoda (crustaceans), Orthoptera (grasshoppers, crickets, katydids), and Isopoda (wood lice and relatives) were not found in the previous survey, but terrestrial habitat near springs was surveyed in addition to aquatic habitat (Springer et al. 2006).

3.2.3. Discussion

In Table 3.2.3-1 we recommend a suite of indicators and measures for future monitoring of water quality in springs and seeps in GLCA. The indicators and measures follow the springs and seeps monitoring protocol established for SCPN parks, which includes GLCA (Perkins et al. 2018). Perkins et al. (2018) outline the three measures of water quantity and three of the four core water quality measures included in Table 3.2.3-1. We added dissolved oxygen because of its importance to aquatic life (Thomas et al. 2006).

Although toxic parameters were not included in Perkins et al. (2018), it is listed as a stressor in Thomas et al. (2006), and the potential threat from mining and mineral extraction in and around GLCA warrants the addition of this indicator given the fact that mineral extraction is already a pressing issue for springs and seeps. Additionally, airborne or atmospheric contaminants, such as

heavy metals or nitrogen fertilizer could impact the quality of springs and seeps. With many of the coal-fired plants closing throughout the region due to economics and cleaner, more cost-effective power generating sources, this may also reduce the amount of airborne pollutants. As previously described, springs and seeps may transport pollutants to surface waters, some of which may be deposited through atmospheric deposition and leaching into aquifers (O'Driscoll et al. 2019).

Table 3.2.3-1. Proposed study details for water quality of springs & seeps.

Potential Indicator	Potential Measure	Potential Reference Criteria for Measure
Water Quantity	Discharge (median and range of stage or flow)	No declines in discharge.
	Variance of Stage or Flow	Flows vary by season and year, but overall patterns are stable.
	Length of Flowing Channel	Length of wetted channel varies by season but remains stable across seasons.
Core Parameters	pH (median and range)	Fewer than 10% of samples exceed the criteria for supported uses (must meet minimum sample size of 10/site).
	Specific Conductance (median and range)	Fewer than 10% of samples exceed the criteria for supported uses (must meet minimum sample size of 10/site).
	Temperature (median and range)	Fewer than 10% of samples exceed the criteria for supported uses (must meet minimum sample size of 10/site).
	Dissolved Oxygen	Fewer than 10% of samples exceed the criteria for supported uses (must meet minimum sample size of 10/site).
Toxic Parameters	Uranium, Nitrates and Nitrites, and Trace Metals (especially mercury)	Fewer than two exceedances of acute and/or chronic criteria (must meet minimum sample size of 4/site). May include other measures that would indicate groundwater issues.
River Invertebrate Prediction and Classification System Benthic Macroinvertebrates	Ratio of Expected to Observed Taxa	Mean observed/expected score ≥ 0.76 for < 3 samples or ≥ 1 sample collected over 8 years.

We also included aquatic macroinvertebrates as an indicator of water quality. Although not part of the springs and seeps protocol, this indicator is listed as a vital sign in Thomas et al. (2006). There are literally hundreds of indices for aquatic macroinvertebrates (Brasher et al. 2011). The River Invertebrate Prediction and Classification System proposed in Table 3.2.3-1 is used by the Utah Department of Environmental Quality (UDEQ) for the state's water resources (UDEQ 2018). Although UDEQ includes springs as a surface water resource, the model is generally used for river systems. Applying the model to spring ecosystems requires gathering data from a variety of reference sites to encompass the wide suite of spring ecosystems present in GLCA, which may not be realistic (Brasher et al. 2011). Other potential metrics include richness and abundance by feeding and habit

groups as well as overall measures of abundance and richness (Brasher et al. 2011). In the macroinvertebrate summary included in this gap analysis, abundance data were not available, but this is an important component to determining composition and diversity.

Trampling (dark spot in the middle of the photo), loss of vegetation, and poor water quality occurred at French spring in the Orange Cliffs from feral burros. Image Credit: NPS.

Weissinger et al. (2012) used richness, species composition across taxonomic, functional feeding, and tolerance groups to determine whether a relationship exists between aquatic macroinvertebrates and disturbance at springs. They found significant differences in macroinvertebrate communities disturbed by livestock use and motorized traffic, but more research is needed to determine how macroinvertebrates vary with disturbance and pollution. In an analysis of 100 springs on the Arizona Strip (the area north and west of the Colorado River in the State of Arizona), the Grand Canyon Wildlands Council (GCWC) (2002) found that the "main controls on invertebrate populations…are elevation, presence and depth of open water, and extent of site manipulation."

Grazing is authorized and widespread in GLCA, including feral cattle horses and burros in some cases, and whether there should be adjustments to the number of grazers and location where cattle are allowed to graze could include the factor of the level of disturbance exhibited at springs. Although

we did not find differences in core water quality measures (other than specific conductance) for springs accessible versus inaccessible to non-native grazers, more study is needed to confirm this finding. For instance, because a site is accessible does not mean that it has been disturbed by grazers, and the level of disturbance may differ depending on the number of grazers that access a site. It's important to note that springs on the Colorado Plateau appear to be adapted to some level of disturbance (Weissinger et al. 2012), and grazers maintain open water, which is important for aquatic life (Kodrik-Brown and Brown 2007). Recent surveys at French Spring in the Orange Cliffs (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, pers. obs. October 2020) show significant impact to the spring from feral burros, including trampling, loss of vegetation and poor water quality.

Recently, Spence (2018) implemented a threats assessment for springs (see the Springs & Seeps condition assessment for more details). Of the 29 springs sampled, 65% were Functioning Intact, 23% were Functioning At-Risk, and nearly 7% were Degraded. Non-native species and livestock were the two most cited causes for degradation. Springs classified as Functioning At-Risk should be given higher management priority to prevent further loss of quality, and Degraded springs could be restored or better protected.

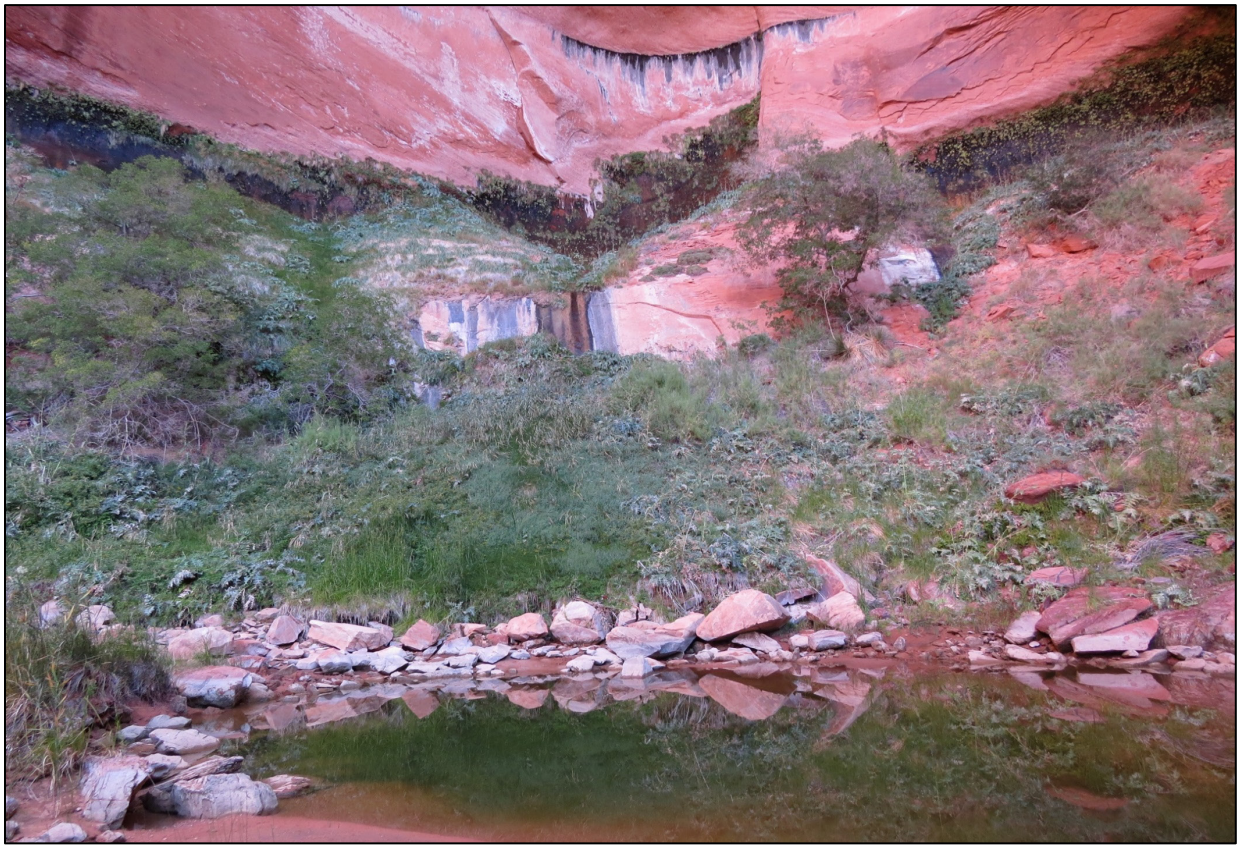
Management actions to protect water quality at springs may include fencing that excludes ungulates but allows access for smaller native mammals. Fencing would reduce erosion, spread of non-native species, and trampling of vegetation (Davis et al. 2017). Management options also include controlling non-native aquatic invertebrates (e.g., crayfish (*Orconectes virilis*), especially in and around Lake Powell) and rehabilitation of spring orifices to improve flow (Davis et al. 2017; Stevens et al. 2016). To mitigate declines in discharge, perhaps installing mechanisms that pool and direct water may maintain spring ecosystems (Stevens et al. 2016). More frequent livestock water tank maintenance and repairs will also increase the amount of water easily accessed by livestock and native ungulates.

3.3. Springs & Seeps (Condition Assessment)

3.3.1. Background & Importance

Springs and seeps, as well as other geographically isolated water resources (e.g., tinajas), are hotspots of biodiversity (Davis et al. 2017; Cartwright et al. 2020; Springer and Stevens 2009; Weissinger et al. 2012). In and around GLCA, springs and seeps support hundreds of plants, many of which are endemic or relict species (Spence 1995, 2005, 2008; Springer et al. 2006; Fowler et al. 2007); a suite of terrestrial and aquatic invertebrates (Springer et al. 2006); and numerous species of amphibians (Nowak and Persons 2008; Stevens et al. 2020). On a broader landscape scale, springs and seeps provide important habitat for breeding and migratory birds and serve as reliable sources of water for a variety of mammals (Cartwright et al. 2020; Spence et al. 2011).

Springer and Stevens (2009) describe 12 types of springs that differ in how groundwater moves through rock and emerges at the surface. Most of these spring types are found in and around GLCA, including springs emerging into stream channels (rheocrene), springs emerging from multiple sources on slopes (hillslope), springs emerging from low gradient wetlands (helocrene), and springs emerging from a confined or unconfined aquifer in pools (limnocrene) (Springer and Stevens 2009).



Hanging garden in an unnamed canyon off of Lake Powell near the San Juan River confluence. Image Credit: NPS.

Hanging gardens are an especially species-rich type of spring whereby water "emerges horizontally along a geologic contact along a cliff wall of a perched, unconfined aquifer" (Springer and Stevens 2009). This spring type is common on the Colorado Plateau and in GLCA in particular, but rare elsewhere in the U.S. (Perkins et al. 2018). The persistence of these groundwater-dependent ecosystems is critical to maintaining the full range of endemic and relict plant species in and around the NRA, as well as supporting other wildlife and plants (Cartwright et al. 2020, Davis et al. 2017).

3.3.2. Study Framework

We mapped all springs and seeps with location information using data provided in published reports (Taylor et al. 1997; Taylor et al. 2004; Springer et al. 2006); in GLCA's springs database (NPS GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mailed park file to Lisa Baril, Utah State University, 18 December 2020); and in online databases, including the Spring Stewardship Institute (2020), USGS National Hydrography Dataset (NHD) (USGS 2020b), and the USGS National Water Information System (NWIS) data (USGS 2020c). Springs were classified as either confirmed or unconfirmed. Several early reports also reference springs and seeps in GLCA but provide no location information (Cooley 1965; Hand 1979 as cited in Huntoon 1979; Williamson 1985). Some of these are likely springs surveyed in more recent studies, but springs were referred to differently in each survey, which made determining redundant springs difficult. Additional GLCA spring reports and studies include Spence (1995, 2004, 2005, 2008) and Fowler et al. (2007).

The indicators, measures, and reference criteria used to evaluate springs and seeps in GLCA are summarized in Table 3.3.2-1. The native plant distribution and occurrence indicator of condition measures are similar to those chosen for monitoring springs across the Colorado Plateau. For example, Perkins et al. (2018) include native species richness and wetland status of native species as potential metrics to inform species composition at springs in Colorado Plateau parks. We considered a widespread distribution of total native, endemic, and relict species as reference criteria because well-distributed plant species indicate dispersal and the occurrence of multiple sub-populations, which reduces the risk of regional extirpation due to the loss of one or a few springs. Relictual species "are species descended from once widespread taxa, whose habitats contracted over time due to environmental changes constraining present-day distributions" (Cartwright et al. 2020). In GLCA, relict species are high elevation species that are now restricted to lower elevation areas due to range contractions since the Pleistocene (Spence 2018). The springs impacts reference criteria were drawn from Spence (2018) threats assessment and from information provided in the NPS springs database.

Data were summarized by spring type, local geology, and watershed. Because hanging gardens are a particularly unique type of spring, this assessment emphasizes that type. Data to assess these measures were obtained from GLCA's springs database, which includes information for 189 springs sampled from 1992 to 2020. Threats assessment criteria were applied at 29 springs beginning in 2012.

Table 3.3.2-1. Study details for the springs & seeps condition assessment.

Indicator of Condition	Measure	Reference Criteria for Measure
Native Plant Distribution and Occurrence	Native Species	Native species are dominant in springs, and are represented by the appropriate species based on species wetland status (e.g., obligate or facultative wetland species)
	Endemic Species	No declines in endemic plant species across springs, based on presence and abundance (these are the criteria that the SCPN and Northern Colorado Plateau Inventory & Monitoring Network Vital Signs are using)
	Relict Species	No loss of relict species presence across springs, although abundances may fluctuate over time
Impacts	Climate and Discharge	Moderate, minor, or no flow alterations evident.
	Development and Human Disturbance	May be up to 50% of water capture (development) and minor trampling.
	Ungulate Effects	Moderate, minor or no signs of domestic livestock
	Non-native Invasive Plant Species	<10% cover
	Erosion and Stability	Signs of previous headcutting or accelerated erosion but currently stable.
	Fire	Fire evidence in surrounding uplands, minor impacts to wetland or no sign of fire but plants species that carry fire are present
	Flooding Disturbance	Some flooding likely or present, <10% cover loss from scour of vegetation
	Uplands Landscape Matrix	Moderate sediment/debris input or Non-native invasive upland non-native plants in site, <10% cover

3.3.3. Data & Methods

Using the abovementioned datasets and reports, we mapped all spring locations in GLCA. Springs that were visited at least once were considered confirmed. All other springs were mapped as unconfirmed. Each unconfirmed location was rated as high, medium, or low depending on the likelihood that the location represented an actual spring. The criteria included 1) local geology, 2) visual interpretation of aerial imagery, and 3) whether the spring was named in the referenced database. Springs are most likely to occur along the Navajo-Kayenta interface, Kayenta Sandstone, Navajo Sandstone, Cedar Mesa Formation, or Chinle Formation (Graham 2016). To evaluate whether riparian/wetland vegetation occurred at an unconfirmed spring, we used 2018, 1-m (3.3-ft) natural color aerial photos obtained from the NAIP (USDA 2020a). Springs with low likelihood met none of the criteria; springs with medium likelihood met at least one criterion; and springs with high likelihood met at least two criteria. Finally, we expected some overlap in spring locations among the various datasets and reports. To resolve duplicate locations, we relied on matching site names,

exactly overlapping locations, and locations that were near but not directly overlaid with other springs but had the same site name and description in reports or databases.

GLCA staff (NPS GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mailed park file to Lisa Baril, Utah State University, 18 December 2020) provided an excel database containing all information collected on a variety of spring types since the early 1990s. The database included metadata for 192 springs and vegetation data for 185 springs. Note that four additional springs were surveyed August 2020. These springs were included in the map and geodatabase but were not included in analyses since those data were received after this assessment was written. Using these data, we compared total native richness to richness of non-native species and richness of wetland plants to determine dominance of appropriate plant species at springs. Wetland plant status for each species was provided in the NPS springs database but was derived from the U.S. Department of Agriculture's PLANTS database (USDA 2020b). Plants are classified into one of five categories depending on their association with wetlands. In this assessment, obligate wetland and facultative wetland species were combined to represent wetland associated species. Obligate wetland species "almost always occur in wetlands," and facultative wetland species "usually occur in wetlands but may occur in non-wetlands" (USDA 2020b). The remaining three classes, facultative (occurs in wetlands and non-wetlands), facultative upland (usually occurs in non-wetlands), and upland (almost never occurs in wetlands) species were considered non-wetland plants.

The eight measures of impacts evaluate various aspects of climate, natural disturbance, and anthropogenic disturbance to spring ecosystems (Spence 2018). Each of the 29 springs were rated on a scale from 0 (no impact) to 4 (high impact). All scores for each spring were added to arrive at a cumulative score for that spring. The cumulative score ranged from 0 to 32 and was divided into four categories of spring function (Table 3.3.3-1). We summarized the 29 springs by the overall assessment score and by individual measures to determine which factors impacted springs the most.

Table 3.3.3-1. Functional categories for springs & seeps impacts.

Score	Category	Description
0–8	Intact	Functioning spring, mostly natural background disturbance
9–17	Functioning At-Risk	Altered disturbance regimes present, some wetland declines
18–24	Degraded	Loss of much of function and stability, leading to erosion and spring loss
25–32	Non-Functional	Severely degraded, most functions and biotic elements lost

3.3.4. Results & Discussion

There are 250 confirmed springs in GLCA, 11 of which are probably duplicate springs, but we could not resolve that issue based on available data (Figure 3.3.4-1). Confirmed springs were most often mapped in the Upper Lake Powell Watershed (44%) followed by the Escalante (30%), Lower San Juan (12%), and Lower Lake Powell (10%) watersheds. Most (63%) confirmed springs occurred in the Navajo Sandstone and Kayenta Formation. The remaining 37% of springs were spread across 30 other formations, including water, so that no one formation exceeded 4% of the total number of

springs. Because springs were overwhelmingly mapped within two geologic formations, we did not factor this into further analyses.

After removing obvious duplicate locations, we mapped 348 unconfirmed springs within GLCA from the NHD database (no additional unconfirmed springs were mapped in the NWIS dataset). Of the 348 unconfirmed springs, 75 (or 21.6%) were assigned high confidence that they represented actual springs, 175 (or 50.3%) were assigned medium confidence, and the remaining 98 (or 28.2%) were assigned low confidence. In addition to these springs, as many as 300 hanging gardens were inundated by Lake Powell, and it is possible that some of the 348 unconfirmed springs were inundated as well (Cooley 1965; NatureServe 2020a). However, the NHD dataset did not include the dates for when springs were mapped so we could not determine how or if any of the 348 springs were mapped prior to the creation of Lake Powell. In a remote sensing study of the Escalante River Watershed, Thomas (2020) mapped more than 1,000 potential springs in GLCA, some of which will be ground-truthed in 2021. Although it's unlikely that all of these locations represent springs, the exercise suggests that spring-like habitat, which is high in biodiversity, is abundant in this area of the park.

Observers reported 144 native species in the springs surveyed from 1992 to 2018. Richness averaged 14.2 native species per spring. Most were obligate wetland (60.4%) or facultative wetland (23.6%) species. The remaining species were either facultative (15.2%) or facultative upland (0.7%) species. Native wetland species richness averaged 10.8 species across all springs. Mean wetland species richness was highest in the Lower San Juan Watershed (12.7) followed by the Escalante (11.2) and Upper Lake Powell (10.6) watersheds (Figure 3.3.4-2). However, because priority was given to documenting wetland plants at springs, non-wetland species were underreported (NPS GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mailed park file to Lisa Baril, Utah State University, 18 December 2020).

To determine if the appropriate wetland species were present, we compared wetland species presence at GLCA springs to wetland species known to occur park-wide and to regional wetland occurrence on the Colorado Plateau. We found that 93% of all wetland species in GLCA were represented at springs, and 66% of all wetland species across the Colorado Plateau were present at springs. These results suggest that the appropriate wetland plant species were well represented at springs in GLCA. Furthermore, non-native species were rare across springs. Non-native species richness averaged just 1.2 species across all spring sampled, and most springs (82%) contained fewer than three non-native species.

Mean endemic richness was highest in the Lower San Juan Watershed (4.3) and mean relict species richness was highest in the Lower Green Watershed (4.0). Of the seven spring types sampled, mean species richness was highest in limnocrene (18.3), helocrene (16.7), and hanging garden (16.1) springs, but note the small sample sizes for limnocrene and helocrene springs (Figure 3.3.4-3). Endemic richness averaged highest in hanging gardens (3.6) and average relict species richness averaged highest in limnocrene springs (5.5).

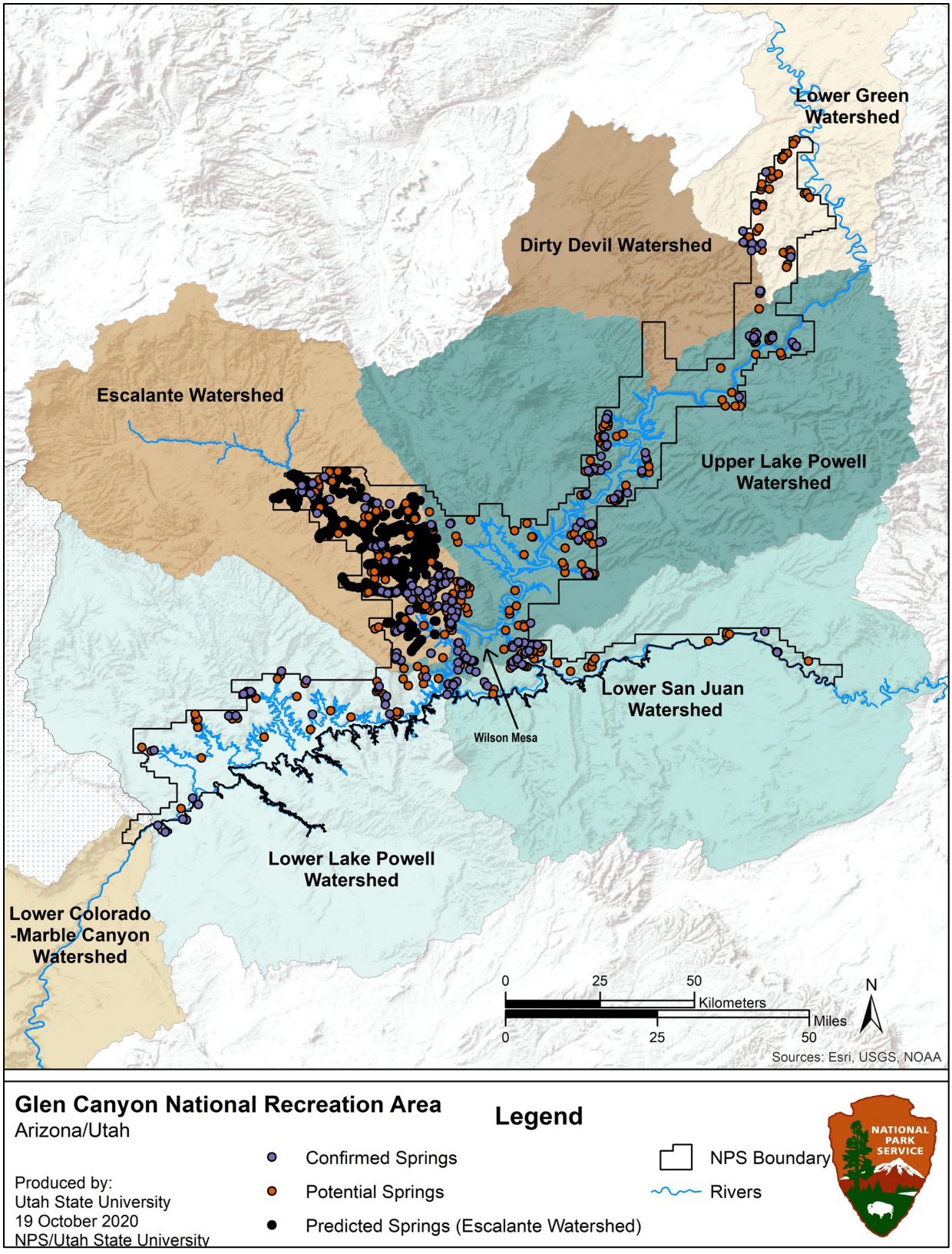


Figure 3.3.4-1. Distribution of confirmed and potential springs in GLCA.

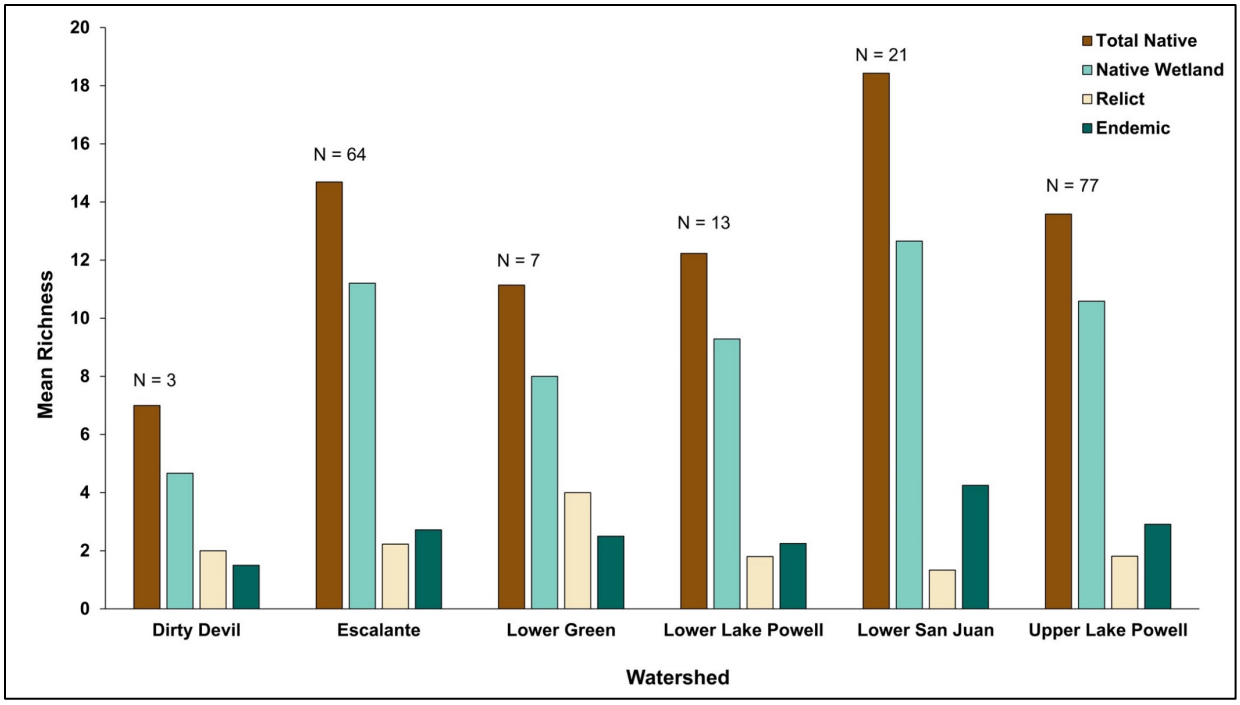


Figure 3.3.4-2. Mean plant species richness by watershed.

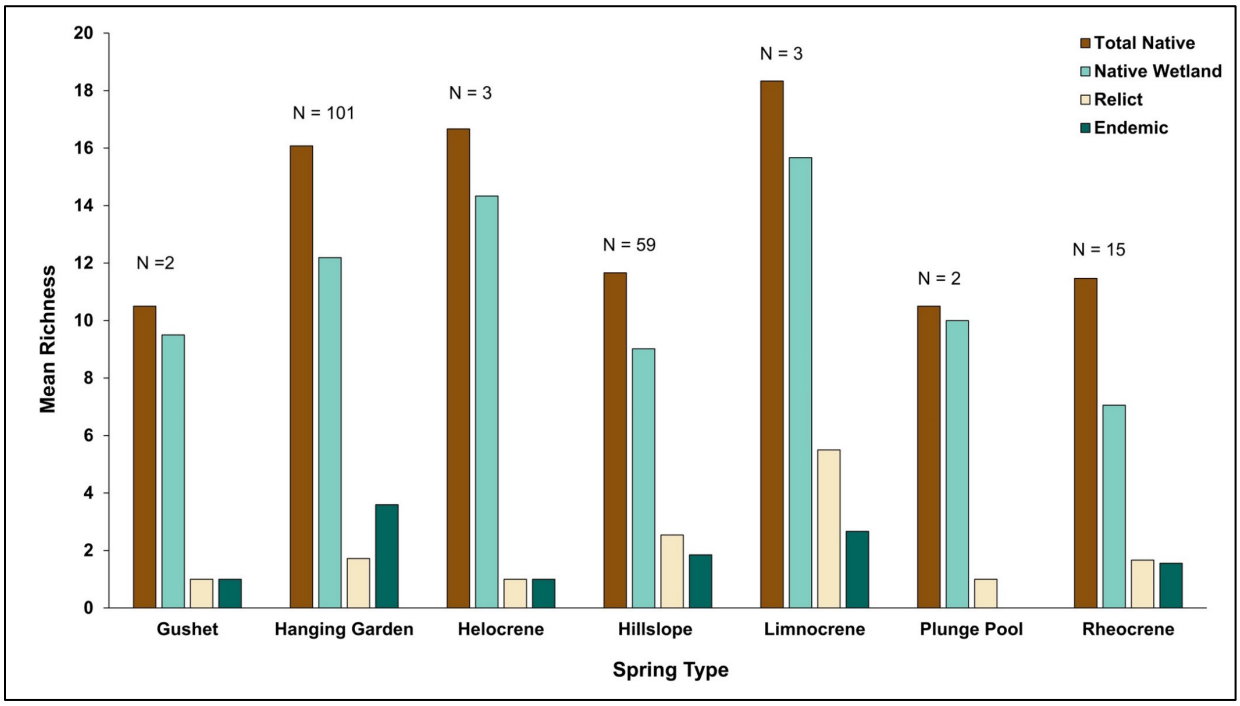


Figure 3.3.4-3. Mean plant species richness by spring type.

Overall, the low occurrence of non-native species and dominance of native wetland species across springs in GLCA suggest good condition for the native plant distribution and occurrence indicator, but we could not determine trends in richness. Limited repeat data on species presence at some

springs reveal no changes in richness from the 1990s to present, but for two springs, one species (a small annual) was absent (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, comments on draft assessment, 20 November 2020). Because 65% of springs were sampled prior to 2000, confidence in the condition rating is medium.

The average impacts assessment score for the 29 springs was 7.4, which falls within the Intact category. However, this average is approaching threshold for Functioning At-Risk springs. A majority (65%) of springs were Intact, while 24% of springs were Functioning At-Risk (Figure 3.3.4-4). No springs were Non-Functional and only 7% of springs were Degraded. Primary issues for Intact springs were non-native plants, drought, and flooding. For Degraded and Functioning At-Risk springs, the primary issues were a combination of livestock, drought, non-native plants, and spring development for livestock watering, which suggests that some management actions may be necessary to protect and restore degraded springs. Overall, the impacts indicator is in fair condition. Trend is unknown and confidence is high because these data were collected recently for a moderate number of springs. Table 3.3.4-1 summarizes the two indicators and trend for this resource.

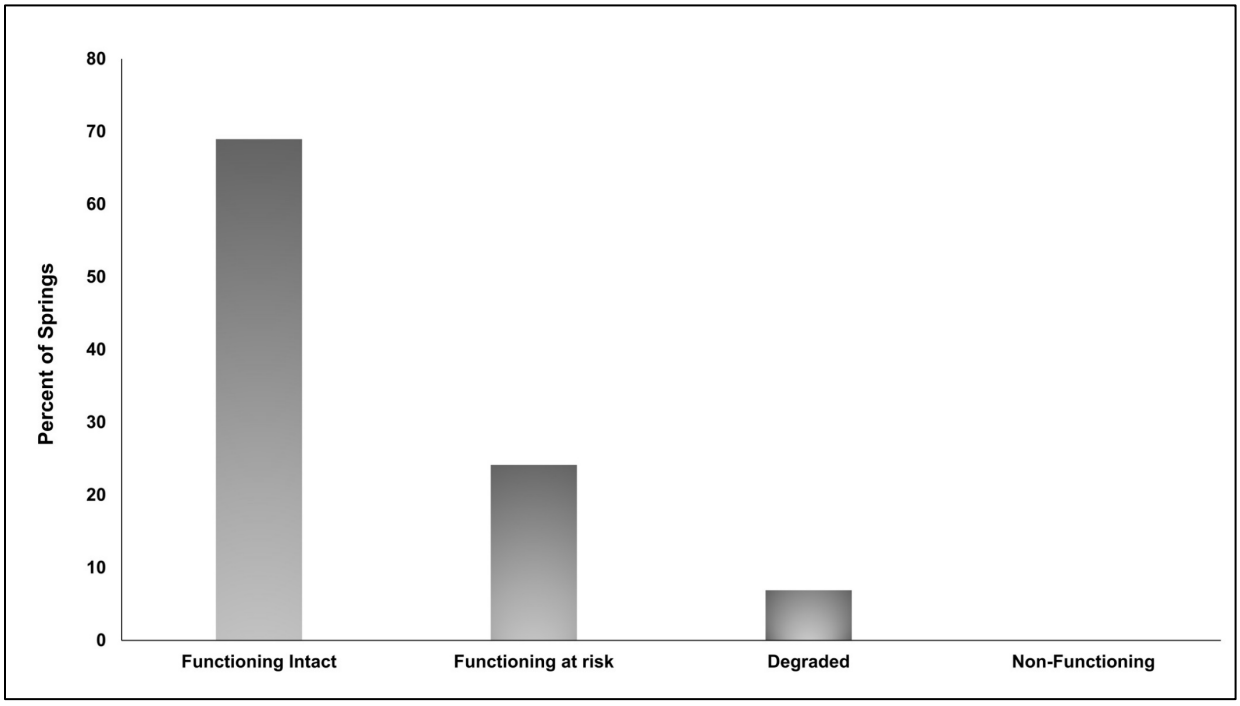


Figure 3.3.4-4. Distribution of 29 springs by functional category.

Although native plant distribution and occurrence is in good condition and impacts are in fair condition, this resource warrants concern owing to its unique niche as biodiversity hotspots, places of plant endemism and relict species, and potential to serve as climate refugia. Because springs and seeps are groundwater-dependent ecosystems, they are more resilient to the effects of climate change than surface water-dependent systems (Cartwright et al. 2020). However, their degree of resilience depends largely on groundwater residence times, which can vary from days to centuries or longer (Solder et al. 2016). Springs supplied by groundwater with long residence times are more likely to

serve as climate refugia in arid regions, but excessive groundwater extraction can reduce resiliency. One study found that groundwater discharge at eight of 19 springs sampled in the Upper Colorado River Basin responded to drought in as little as six months (Solder et al. 2016). This suggests that groundwater residence times may be relatively short for some springs in the region, with response times over decades or less rather than centuries. This is supported by a study of spring discharge response to climate change in Arches NP. Weissinger et al. (2016) found that spring discharge at two springs responded to reductions in 10-year cumulative winter precipitation. For the largest hanging gardens in the Navajo Sandstone, discharge response times are likely 10–15 years at most, and perhaps much shorter (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, comments on draft assessment, 20 November 2020). In the Upper Colorado River Basin, 98% of water for agriculture and municipal use come from surface water, while the remaining 2% comes from groundwater (Maupin et al. 2018). However, as surface water declines and the need for water increases, there is likely to be more pressure on aquifers (Maupin et al. 2018).

Table 3.3.4-1. Springs & seeps condition ratings summary.

Indicator	Condition Rating [1]	Trend	Condition Evaluation
Native Plant Distribution and Occurrence	Good	Unknown	Native species dominate all spring sites with an average of 10.8 wetland species. Although there was variation in wetland, relict, and endemic species across watersheds and spring types, they all exhibited similar richness. Due to large differences in survey sample size, the trend is unknown, and confidence is medium.
Impacts	Fair	Unknown	Since the majority of springs are Intact (68%), but 7% are Degraded, the condition is fair. Trend could not be determined because of the single site visit. Repeat threats assessment of the same springs will allow for trends analyses in the future. Confidence in the condition rating is high.

[1] See Appendix B, Table B-1, for the 5-level condition rating statements for each indicator.

Spring- and wetland-dependent species and species with low dispersal abilities will be the most affected by a declining water supply, but how changes in spring discharge will affect species occurrence depends on ecosystem thresholds. Cartwright et al. (2020) state that thresholds could be crossed when there is 1) a transition from surface water to zones of saturated soil without inundation; 2) shifts in timing of water availability (e.g., seasonal); and 3) reduction in size or connectivity below thresholds to maintain viable populations. As discharge declines, the wetted area of spring ecosystems will shrink. Patten et al. (2008) predict that species that are the least tolerant of drying will be extirpated first. If wetland species persist, they are likely to be severely reduced in cover. These species may be replaced by transition species, or facultative species. If flow ceases altogether, upland species will completely replace wetland species (Patten et al. 2008).

Although thresholds for change in spring ecosystems in GLCA and elsewhere on the Colorado Plateau are unknown (Perkins et al. 2018), other studies have shown that even small declines in

discharge have large effects on spring-fed aquatic environments. In Death Valley NP, declines in discharge led to reduced aquatic habitat volume, increased variability in water temperatures, and reduced suitability for invertebrates that require stable habitat (Morrison et al. 2013). In Owens Valley, California, plant species richness declined, and the community shifted from marsh vegetation to drought-tolerant species at springs because of groundwater pumping (Perkins et al. 1984). A follow-up study in Owens Valley found that vegetation cover also declined, and wetland plants experienced greater mortality (Sorenson et al. 1991). In addition, Weissinger et al. (2016) found that monthly increases in potential evapotranspiration corresponded to lower discharge at three springs in Arches NP, which is likely to stress wetland-dependent plants.

Granddaddy hanging garden in Ribbon Canyon. Image Credit: NPS.

Spence and Cushing (2019) formulated four potential climate change response scenarios for spring ecosystems in GLCA. The main assumption in all four scenarios is that discharge will decline due to reduced snowpack and warmer temperatures, but over what period remains uncertain. If aquifer declines are slow, then springs are likely to remain stable, at least for a time. At the other extreme, a rapid decline in discharge may result in collapse of spring ecosystems (Spence and Cushing 2019). Many endemic plant species found at GLCA springs generally occur within a narrow elevation band from 1,000–2,000 m (3,281–6,562 ft) above sea level. Above 2,000 m (6,562 ft), hanging gardens and associated geology become rare. For example, nearly all (90%) confirmed springs are located below 1,555 m (5,102 ft), while only three springs occur above 2,000 m (6,562 ft). Based on the distribution of springs in GLCA and predicted elevational shifts in temperature, Spence and Cushing (2019) estimate that 77% of springs and 80% of hanging gardens will experience temperatures above the threshold of endemic plant species by 2100 under an intermediate climate scenario. However, variability in microclimate across springs may ameliorate climate change effects.

Weissinger et al. (2016) recommended "prioritizing deeply shaded, north-facing, and/or higher-elevation springs for protection and restoration." Approximately 30% of hanging gardens in GLCA are either deeply shaded alcoves or north-facing (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, comments on draft assessment, 20 November 2020). These springs are likely to be less vulnerable to increases in temperature. In addition to the microclimate characteristics suggested by Weissinger et al. (2016), Cartwright et al. (2020) include consistent discharge, long groundwater residence times, and few localized threats from disturbances, among other characteristics as important in evaluating a spring's ability to serve as a climate refugium.

Cartwright et al. (2020) also predict that springs supporting relict species are more likely to serve as climate refugia than those without (Cartwright et al. 2020). The presence of relict species indicates that these springs served as refuges in the past. Of the 185 springs surveyed in GLCA, 115 support at least one relict species, 101 of which also support at least one endemic species (there are 24 relict species distributed across the 115 springs). Of the 14 endemic species documented in springs, 13 would be preserved if all springs supporting relict species persisted. *Carex specuicola* was the only species not reported at a spring that contained at least one relict species. However, the relatively low relict (1.8) and endemic (2.7) mean species richness across springs suggest that efforts to protect springs should be widespread to conserve the whole suite of species.

Although managing groundwater resources is generally not within the purview of the NPS (Lake Powell is the major driver of groundwater flow locally, and the lake level is managed by the Bureau of Reclamation), park managers can address issues at the spring itself. One survey found that 90% of 103 springs on the Arizona Strip were disturbed by livestock, human development, or game use (Grand Canyon Wildlands Council 2002). Similarly, in Nevada, 78% of springs were affected by human disturbance (Sada et al. 2005). Even springs in apparently protected areas such as national parks face threats from disturbance. Of 192 springs surveyed in GLCA, 32.3% are accessible to cattle but only 18.8% have been exposed to recent cattle disturbance (NPS GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mailed park file to Lisa Baril, Utah State University, 18 December 2020). Grazing allotments are widespread in GLCA (BLM 2015), but because of the

location of many springs in steep side canyons, most are inaccessible to cattle, horses, or burros even if they are contained within a grazing allotment (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, comments on draft NRCA, 14 October 2020). Of the springs that are accessible, downcutting of channels, soil deposition, and nitrogen enhancement are all potential threats to spring ecosystems (Davis et al. 2017).

A hillslope spring, Immigrant spring, in Silver Falls Canyon, Escalante District. Image Credit: NPS.

Fencing to exclude ungulates (but that allow for smaller native mammals) would reduce erosion, spread of non-native species, and trampling of vegetation (Davis et al. 2017). More frequent livestock water tank maintenance and repairs will likely increase use by livestock and native ungulates, which may reduce the use of water in natural springs Management options also include controlling non-native plants and invasive aquatic invertebrates, assisted migration for dispersal-limited species, and rehabilitation of spring orifices to promote flow (Davis et al. 2017; Stevens et al. 2016). To mitigate declines in discharge, perhaps installing mechanisms that pool and direct water may be beneficial to support all life forms that depend on these systems for freshwater (Stevens et al. 2016). While erosion is a natural physical process that is responsible for creating hanging gardens, falling rocks that crush vegetation, including endemic and relict plants, are common in some hanging gardens (Stevens et al. 2016).

The springs monitoring protocol for SCPN parks (Perkins et al. 2018) and for GLCA (Spence 2018) call for estimating cover of individual species at springs. Cover was not a metric we could assess with the available data, but future collection of this metric would help inform changes in plant species composition due to aquifer depletion, recreation use, non-native species, grazing, and climate change (Perkins et al. 2018). Perkins et al. (2018) recommend a minimum sample size of 25 hanging gardens with similar geology and source aquifer and sampling of sentinel sites for more regular monitoring with multiple annual site visits. The implementation of these protocols will eventually show how springs are changing. Currently, the SCPN is in the process of monitoring around 20 hanging gardens and other springs in the Wilson Mesa region on the lower San Juan Arm within the Lower San Juan Watershed where numerous springs exist. In 2019, field work commenced with sampling at 5 springs. The project plans to utilize a panel design with a 4-year rotation, sampling around 25% of the springs each year.

Given the importance and complexity of spring ecosystems, this resource may warrant a more intensive study to address existing data gaps, such as sources and residence times of groundwater given the importance and complexity of spring ecosystems, future climate change scenarios, levels of endemism, and the high degree of uncertainty on the persistence of spring ecosystems in GLCA.

3.4. Riparian Zone (Condition Assessment)

3.4.1. Background & Importance

More than 4,900 km (3,045 mi) of perennial and intermittent waterways flow through GLCA (NPS 2020a). These river miles (excluding dry washes and ephemeral streams) are distributed among five major perennial rivers, five smaller perennial streams, and 32 intermittent streams. The number of perennial river and stream miles account for just under 5% of all waterways in GLCA, while the remaining 95% are intermittent or ephemeral (NPS 2020a). The amount of water in the rivers and streams depends on the amount of annual snowpack accumulated in the surrounding, and in some cases far distant, mountains and rate of melt in spring and summer. Monsoon rains, intermittent precipitation, water from springs & seeps, and in some instances, livestock ponds also contribute to flows but to a lesser extent than snowpack (NPS 2014). Riparian plant communities range from cattail/rush/sedge marshes, streamside facultative species such as willows, to deciduous forests, which include water-dependent woodlands and shrublands (Tendick et al. 2017). Associated riparian plants provide habitat for a multitude of wildlife and insect species in GLCA, supplement floodplain diversity and complexity, add channel stability, provide shading of streams by overhanging vegetation, which reduces stream temperature, and provide cover and habitat for fish (NPS 2014).

GLCA is a member of the Escalante River Watershed Partnership, which works to restore conditions to a healthy functioning watershed. An example of this work is the control of Russian olive along the Escalante River by the Utah Conservation Corps work crew. Image Credit: NPS.

3.4.2. Study Framework

The scope of analysis for this assessment includes four major tributaries to the Colorado River (Dirty Devil, Escalante, Halls Creek, and Lake Canyon), as well as two tributaries to the Escalante River (Coyote Gulch and Harris Wash) and one tributary to the San Juan River (Wilson Creek), which are all perennial. We selected three indicators of condition that address different aspects of stream health, including water quantity and availability, stream/watershed health, and vegetation (Table 3.4.2-1). The indicators, measures, and reference criteria were derived from Scott et al. (2005), who characterizes healthy riparian ecosystems on the Colorado Plateau as those with high flow variability resulting in plant communities dominated by native species.

Table 3.4.2-1. Study details for the riparian zone condition assessment.

Indicator of Condition	Measure	Reference Criteria for Measure
Water Quantity and Availability	Flow Variability	No declines in peak and annual flow and no changes in timing of peak flow
	Water Presence and Persistence	No declines in wetted extent
Stream/ Watershed Health	Aquatic Intactness	Moderately high, high, or of very high aquatic intactness
	Impairments	No chronic impairments for the subset of streams analyzed
Vegetation	Departure from Natural/Historical Condition	Riparian vegetation across the majority of stream reaches analyzed is intact and represents minor departure (10–33%) from historical conditions.
	Non-native Plants Presence/Absence	Non-native plants may be present, but species that have the greatest negative impact on ecosystem structure and function are absent.

The area of analysis for water quantity and availability and vegetation indicators was a 175-m (574-ft) buffer created on both sides of the USGS NHD dataset (USGS 2020b) subset to the streams listed above because this is the maximum width of the valley bottoms that can potentially support riparian vegetation as modeled by Woodward et al. (2018). The area of analysis for the stream/watershed health indicator was the USGS hydrologic unit code 6 (HUC6) subwatersheds (USGS 2020b), which are the smallest watersheds mapped by the USGS.

3.4.3. Data & Methods

Of the streams included in this assessment, hereafter referred to as subset streams, USGS stream gage data were available for the Dirty Devil (gage ID: 09333500) and Escalante (gage ID: 09337500) rivers (USGS 2020c). Both gages are located outside of GLCA's boundary. There are no gages located on Wilson Creek, Halls Creek, Lake Canyon, Coyote Gulch, or Harris Wash. Annual discharge data were available from 1948 to 2020 for the Dirty Devil and from 1943 to 2020 for the Escalante. Peak flow data were available from 1948 to 2018 for Dirty Devil and from 1910 to 2019 for the Escalante. We analyzed these datasets for trends in annual discharge, peak discharge, and timing of peak discharge.

Laub et al. (2018) identified historical (or reference) ranges for the Escalante and Dirty Devil rivers that occurred prior to large-scale water development. The reference period for the Dirty Devil River included a 10-year period from 1948 to 1957, and the historical period for the Escalante River spanned a 13-year period from 1943 to 1955 (Laub et al. 2018). We compared USGS discharge data for the historical range to the most recent (2008–2019) ranges available for April to October, as well as a comparison to total annual flow (USGS 2020c). Discharge data were log transformed to meet the assumptions of normality for regression analyses.

Although stream gage data were not available for the other streams, Wilkowske et al. (2011) developed a method for estimating monthly and annual streamflow for ungauged sites in Utah. We accessed the modeled data from the USGS StreamStats web interface (USGS 2016). The output includes mean annual flow and mean monthly flow in three exceedance values: 80%, 50%, and 20%. Exceedance "refers to the streamflow value that is met or exceeded for a certain percentage of the time" (Wilkowske et al. 2011). "For example, if the 80-percent exceedance value for a given month is 25 ft^3/s, that means that the streamflow at that location exceeds 25 ft^3/s 80 percent of the time for that month." We summarized monthly streamflow estimates using the 80% exceedance values because estimates for this value were more reliable and accounted for the majority of estimated streamflow (Wilkowske et al. 2011). We compared monthly estimates for Halls Creek, Lake Canyon, Wilson Creek, Harris Wash, and Coyote Gulch and looked for estimated patterns typical of streams on the Colorado Plateau, which are characterized by peaks in the spring due to snowmelt and peaks in late summer due to monsoon rains.

Because stream gage data were only available for the Dirty Devil and Escalante rivers, we evaluated water presence and persistence for other streams (in addition to the Dirty Devil and Escalante rivers) using maximum normalized difference vegetation index ($NDVI_{max}$) raster files created by the NASA DEVELOP Glen Canyon Eco Team (Frier et al. 2018). $NDVI_{max}$ raster files were available from 1995 to 2017 and were derived from Landsat satellite imagery with a resolution of 30 m (98 ft). Other studies have shown that NDVI can serve as a proxy for flow (Nguyen et al. 2014; Xu et al. 2016). The 1995 and 2017 raster files were clipped to the riparian buffer. We considered pixels with NDVI values of ≥ 0.2 as riparian vegetation, pixels < 0 as water, and pixels between 0 and 0.1 as "other" (Jeong et al. 2016; Jones et al. 2008; McGwire 2019). We then differenced the images using the raster calculator tool in ArcMap 10.4 and summarized the change classes with the area of analysis. We considered the stream channel to be wetted if riparian vegetation or water was present along the entire length.

A narrow bedrock riparian canyon setting in Harris Wash. Image Credit: NPS.

The Conservation Biology Institute (CBI) developed a model of aquatic intactness for HUC6 subwatersheds across the Colorado Plateau in 2015 (CBI 2015). Aquatic intactness provides an estimate of condition "based on the extent to which human impacts such as water demand, agriculture, urban development, natural resource extraction, dams, diversions, and alterations have disrupted the hydrology, water quality, and habitat quality of aquatic systems" (Bryce et al. 2012). Aquatic intactness scores ranged from very high to very low. While we summarized aquatic intactness scores across all 134 subwatersheds occurring entirely or partially within GLCA, we focused on those HUC6 watersheds that overlapped the subset streams.

Water quality impairment data were downloaded from the NPS Hydrographic Impairment Statistics website (NPS 2020a), which were derived from Utah's Division of Water Quality (UDWQ) (UDWQ 2017, 2020) and Arizona's Water Quality Division (AWQD 2017, 2018). We included impairment statistics for the most recent monitoring cycle (2018 and 2020) as well as data for the previous monitoring cycle (2014 and 2016). Stream impairment data for the current monitoring cycle in Utah are provisional and subject to change (UDWQ 2020). We presented all impairment statistics for GLCA (except for Lake Powell and the Colorado River) but applied the reference criteria to the subset streams.

Modeled riparian vegetation departure data were developed for the Colorado Plateau by the BLM and Utah State University's Department of Watershed Sciences (Macfarlane et al. 2017). The riparian vegetation departure index, which was based on 2012–2015 data, is a ratio of existing vegetation condition to an estimation of pre-European settlement (Macfarlane et al. 2017). Vegetation departure data were available for the Escalante and the two tributaries (Coyote Gulch and Harris Wash) and for a portion of the Dirty Devil from the park boundary to the Red Benches area. No data were available for the remaining streams. The vegetation departure ratio can be converted to a percentage that corresponds to one of four classes of departure: negligible (<10%), minor (10–33%), significant (33–66%), and large (>66%). For the existing vegetation layer (EVT), Macfarlane et al. (2017) used LANDFIRE 2012 EVT Version LF_1.3.0, which is based on a 30-m Landsat satellite classified image. LANDFIRE Biophysical Settings layer was used for historical vegetation, which is based on the biophysical environment and approximation of the historical disturbance regime (Macfarlane et al. 2017).

To address invasive species, we included information about conversion type provided by Macfarlane et al. (2017) in the riparian vegetation departure models. Conversion types included conversion to invasive species, devegetation (removal of vegetation), conifer encroachment, conversion to grass/shrubland, and no change. The invasive conversion type was further refined into minor, moderate, or significant conversion classes. As with vegetation departure, data were only available for the Escalante and the two tributaries (Coyote Gulch and Harris Wash) and for a portion of the Dirty Devil from the park boundary to the Red Benches area. A recent study on the Escalante River (Scott et al. 2018) showed that the invasion of exotic species including Russian olive and tamarisk lead to a series of other ecosystem changes, in particular a narrowing of the stream channel.

For species-specific information on non-native plants, we used data provided by the NPS vegetation mapping effort (Tendick et al. 2017) and the NPS Exotic Plants Management Team (EPMT). We subset the NPS vegetation mapping project data to the two classes in which non-native plants dominated. These two classes were tamarisk (*Tamarix* spp.) shrublands and weedy herbaceous complex (Tendick et al. 2017). The weedy herbaceous complex includes Russian thistle (*Salsola* spp.), camelthorn, cheatgrass, and five-stamen tamarisk (*Tamarix chinensis*). We further subset these classes using the same riparian buffer as described above. Because the NPS vegetation mapping program also collected species cover data, we extracted the plot locations located within the riparian buffer zone and identified the number and location of plots containing at least one of the most problematic non-native species. The EPMT spot-mapped and mapped treatment areas for ravenna

grass, tamarisk, and Russian olive in some locations for future control efforts. Data on locations and treatment area were available from 2009 to 2019 depending on the species. The most problematic non-native species that invade riparian areas in GLCA include ravenna grass, Russian olive, camelthorn, Russian knapweed, perennial pepperweed, and tamarisk (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mailed list of invasive plants, 3 March 2020).

3.4.4. Results & Discussion

There were no significant trends in annual discharge for the Escalante River from 1943 to 2020 (F (1,59) = 3.3, p = 0.08) or the Dirty Devil River from 1948 to 2020 (F (1,60) = 0.002, p = 0.96) hydrographs (Figure 3.4.4-1). Nor were there significant changes in the amount of annual peak discharge for the Dirty Devil (F (1,62) = 3.56, p = 0.06) stream gage, but when excluding the three most extreme records, there was a slight but significant decline (F (1,59) = 4.5, p = 0.04). We did not find a significant trend in peak flow for the Escalante River stream gage from 1910 to 2019 (F (1, 62), p = 0.44). There were no significant shifts in the timing of peak flow for the Dirty Devil River stream gage (F (1,61), p = 0.1) or for the Escalante River stream gage (F (1,62), p = 0.20). Peak flows occurred in July–August most years, and in some years, a second peak occurred in October–November. For the Escalante River (1948–2020), the stream gage did not record any no-flow days (although flow was extremely low for various periods throughout the record); however, no-flows regularly occur in July for the Dirty Devil River (1943–2020).

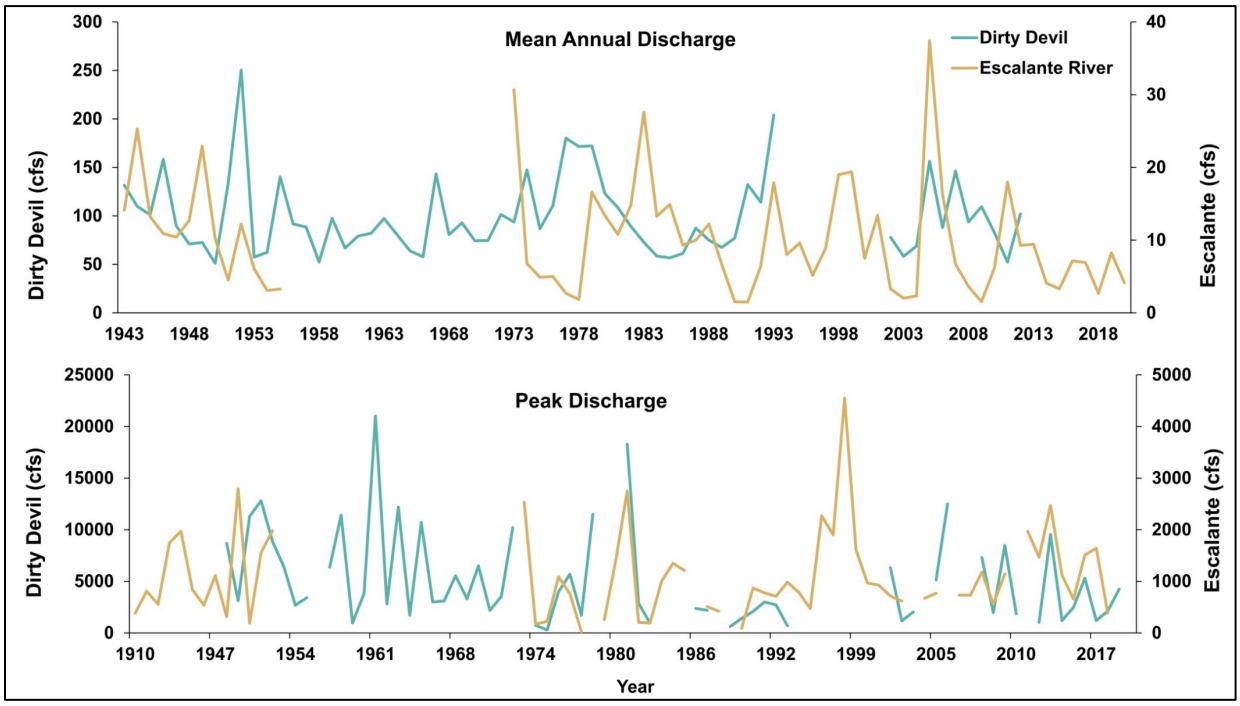


Figure 3.4.4-1. Mean and peak annual discharge for the Escalante River (gage ID: 09337500) and Dirty Devil River (gage ID: 09333500) stream gages.

Boxplots of flow data show that mean annual flow, annual variability in flow, and monthly flow variability were larger during the historical period than during the contemporary period for the

Escalante River (t (24) = 2.21, p = 0.02) but not for the Dirty Devil River (t (18) = 0.52, p = 0.60) (Figure 3.4.4-2). The Escalante monthly hydrograph reflects a snowmelt-driven river while the Dirty Devil River reflects a late summer rain-driven hydrograph.

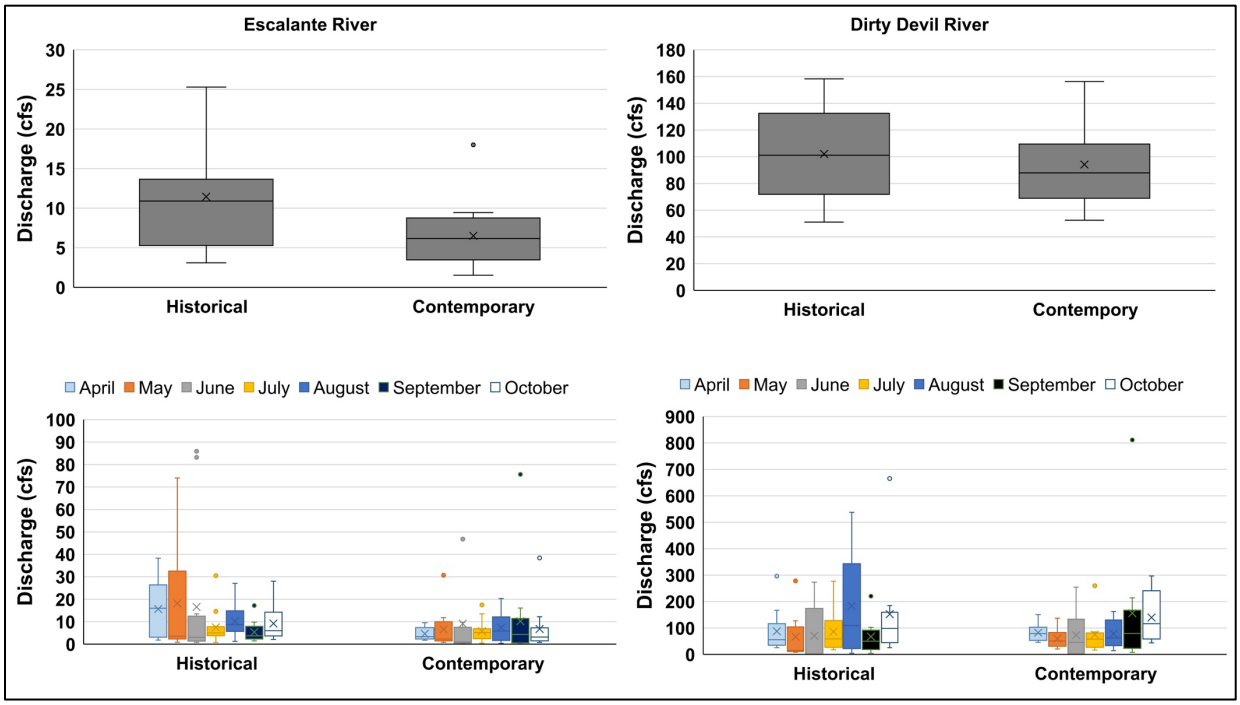


Figure 3.4.4-2. Boxplots showing the mean, median, lower quartile, upper quartile, and outliers for historical and contemporary total annual and monthly (April–October) flow data for the Escalante River and Dirty Devil River USGS stream gages.

For the remaining streams without gages, StreamStats predicted that the lowest 80% monthly exceedances occurred during September to January and that flows increased until July or August. Flows were then predicted to decline throughout the remainder of the year (Figure 3.4.4-3). Mean monthly stream gage data for the Dirty Devil showed peaks in February/March and October/November, with the lowest flows occurring in July. Escalante stream gage data showed a similar pattern to the StreamStats estimates except that peak flows occurred earlier, during May and June. Differences in patterns between the Dirty Devil and Escalante versus the other streams may partially be due to the presence of diversions and dams on those rivers. For the Escalante River gage, low flows are influenced by diversion into Wide Hollow Reservoir approximately 6.4 km (4 mi) upstream and by a diversion of Pine Creek into an off-channel reservoir. It's important to note that much of the inflow for the Escalante River occurs below the stream gage. For the Dirty Devil there are several diversions for tributaries of this river (USGS 2020c).

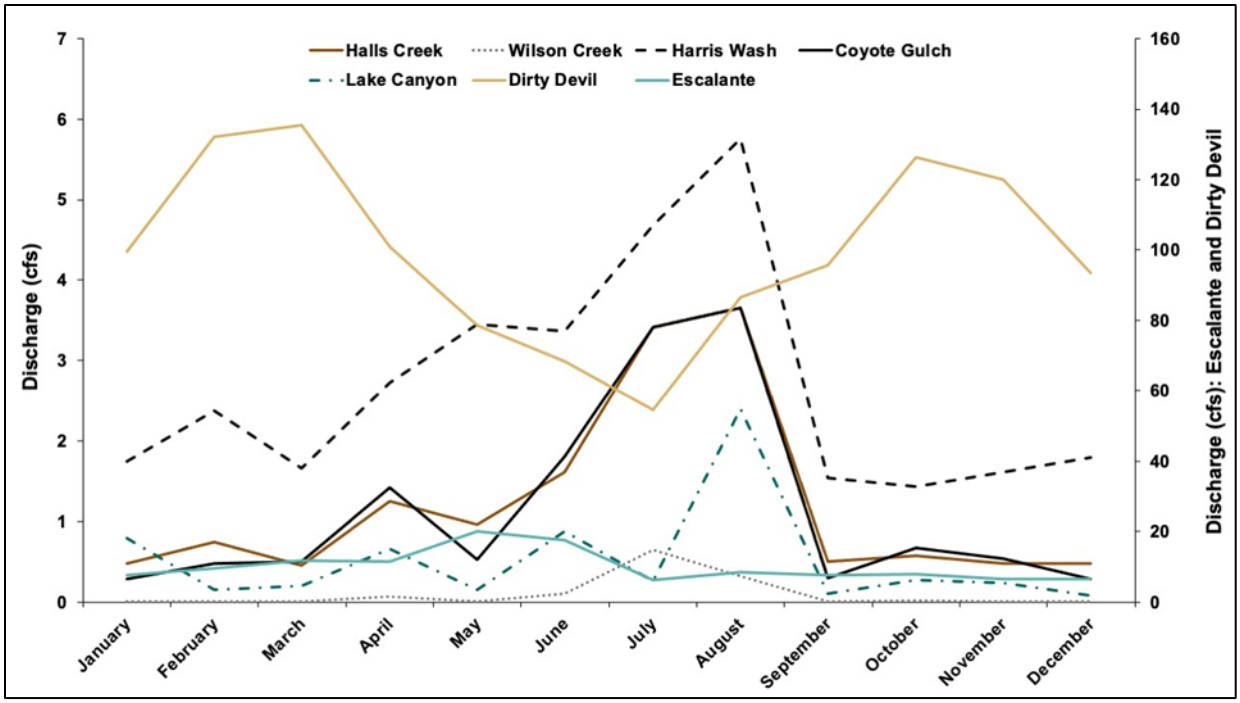


Figure 3.4.4-3. Estimated monthly streamflow for ungauged streams (Halls Creek, Wilson Creek, Coyote Gulch, Lake Canyon) and actual monthly streamflow for the Escalante River (gage ID: 09337500) and Dirty Devil River (gage ID: 09333500).

Although year-to-year variability in runoff is high and is driven mainly by precipitation, no consistent decadal or multi-decadal patterns in precipitation and runoff have been identified for streams on the Colorado Plateau (Lukas and Payton 2020), which makes assessing condition difficult. Stream hydrographs can be highly variable from one stream to another "because of underlying differences in climate, geology, topography, soils, and vegetation cover within a watershed" (Scott et al. 2005). Streams originating on the Colorado Plateau are highly variable and unpredictable compared to streams with headwaters located in the mountains outside the plateau (Scott et al. 2005). The smaller streams included in this assessment are likely driven entirely by episodic precipitation events, which accounts for peaks in late summer, while the larger Escalante River and the spring peak for the Dirty Devil River are driven by snowmelt (Scott et al. 2005) from the mountain ranges in their watersheds.

For water presence and persistence, most (89%) of the area in the riparian buffer did not exhibit any change from one class to another between 1995 and 2017. Of the 11% of the area that did change, 5% was classified as loss of riparian vegetation (<1%) or loss of water (4.6%). Losses occurred along all subset streams, but the greatest losses occurred along Lake Canyon, Wilson Creek, and Halls Creek. In sum, the majority of area did not exhibit any changes in wetted extent, the stream gages for the Escalante and Dirty Devil rivers did not reveal significant declines in discharge, and patterns of streamflow (estimated or actual) indicated a hydrologic regime consistent with expectations for Colorado Plateau streams. However, boxplots of monthly spring and summer discharge revealed a moderate departure from historic/reference criteria, especially for the Escalante River in April and

May. Furthermore, the wetted extent for some streams, in particular the Dirty Devil River, is dominated by non-native and invasive plants. The available data for the water quantity and availability indicator suggest that the condition is fair. Trends have deteriorated. Confidence is medium because some of the information was estimated.

Of the 134 HUC6 watersheds partially within or entirely within GLCA, most were rated as moderately low (35.8%), moderately high (27.1%), or high (17.2%) in aquatic intactness (Figure 3.4.4-4). Few were rated as very high (3.7%) or very low (6.0%). The rivers and streams of interest in this assessment (i.e., Dirty Devil, Escalante, Halls Creek, Lake Canyon, Coyote Gulch, Harris Wash, and Wilson Creek) flow through 18 HUC6 subwatersheds. All but four were rated as high or moderately high aquatic intactness. The lower reach of Halls Creek where it joins the Colorado River, the upper Escalante River where it crosses the park's boundary, and the upper Dirty Devil River at the park boundary were rated moderately low. Of the 4,900 km (3,045 mi) of streams in GLCA, 238 km (148 mi), or 4.9%, are designated as impaired. However, none of the rivers and streams in the scope of analysis for this assessment were impaired (Table 3.4.4-1). Based on these results, the condition of stream/watershed health is fair. Trends are unknown, but confidence in the condition rating is medium because although stream impairment data are recent, the modeled aquatic intactness provides a single estimate of condition based on data availability, which varied by subwatershed (Bryce et al. 2012).

Only 58% of the total lengths of the Dirty Devil, Escalante, Coyote Gulch, and Harris Wash were analyzed for departure from natural conditions. However, the majority of the riparian zones assessed have experienced large or significant departures (Figure 3.4.4-5). Most changes (59–77%) were considered minor to moderate conversions to invasive plants. The NPS vegetation program mapped tamarisk shrublands in 489 ha (1,209 ac), or 5.8% of the area within the riparian area of the subset of streams included in this assessment. Weedy herbaceous complex was mapped in 83 ha (205 ac), or 1% of the buffered areas. One or both classes were mapped on all streams except Wilson Creek. Tamarisk shrublands were mapped along almost the entire length of the Dirty Devil River, accounting for 41% of tamarisk shrublands mapped in the buffer zone. The remaining areas were mapped along the Escalante River and Halls Creek, with smaller non-native patches mapped in the upper reaches of Lake Canyon.

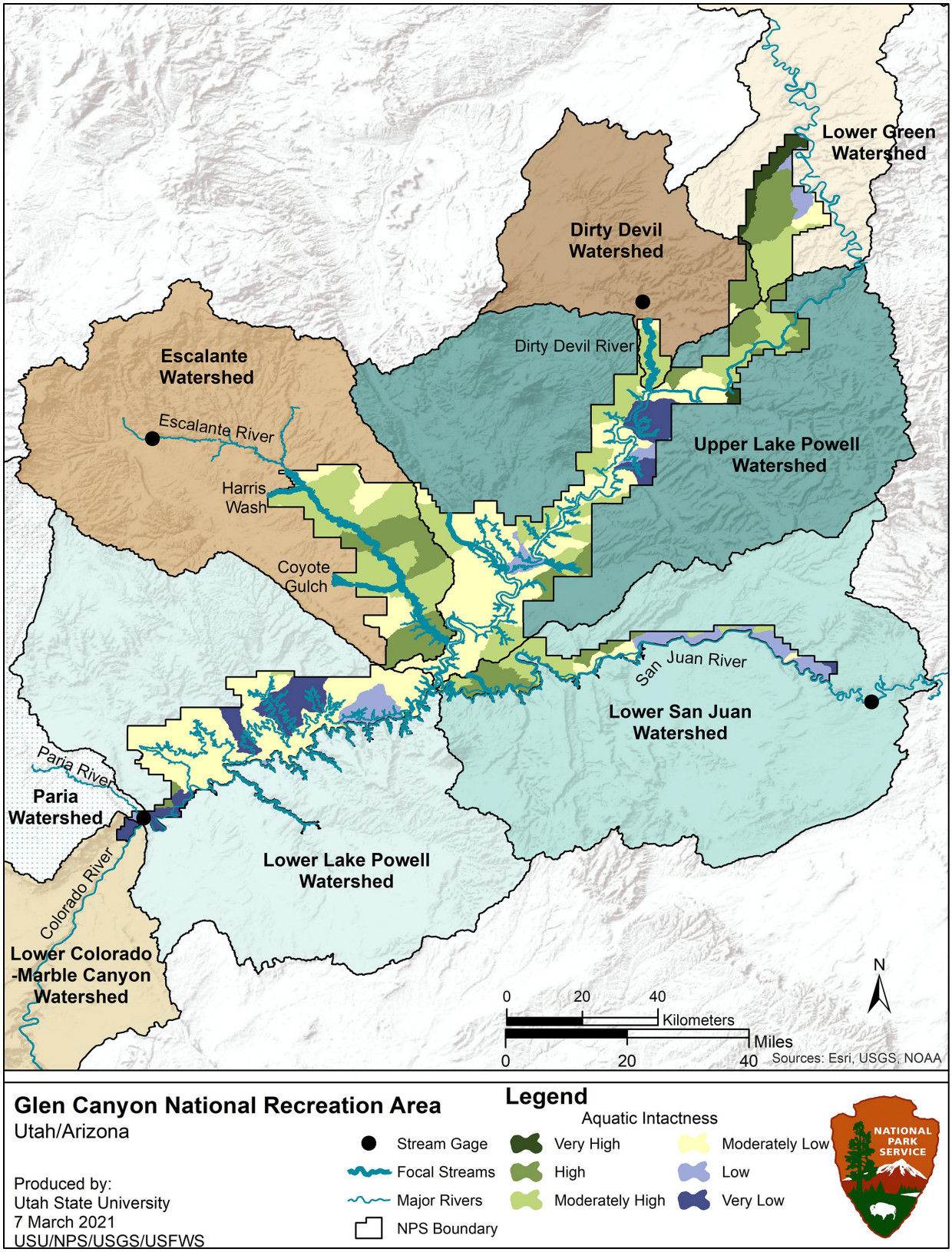


Figure 3.4.4-4. Aquatic intactness for HUC6 subwatersheds.

Table 3.4.4-1. List of water quality impairments for perennial streams in GLCA excluding the Colorado River and Lake Powell.

Watershed	Assessment Unit	Impairments 2014/2016	Impairments 2018/2020
Lower Lake Powell	Wahweap Creek	Selenium, maximum temperature, total dissolved solids	Total dissolved solids, maximum temperature
	Last Chance Creek	Benthic macroinvertebrates, total dissolved solids	Benthic macroinvertebrates, total dissolved solids
Lower San Juan	San Juan River-1	Aluminum, copper, oxygen, iron, mercury	Maximum temperature, *E. coli*
	San Juan River-1 Tributaries	Total dissolved solids	Total dissolved solids
Paria	Paria River	*E. coli*, selenium, suspended solids	*E. coli*, selenium, suspended solids

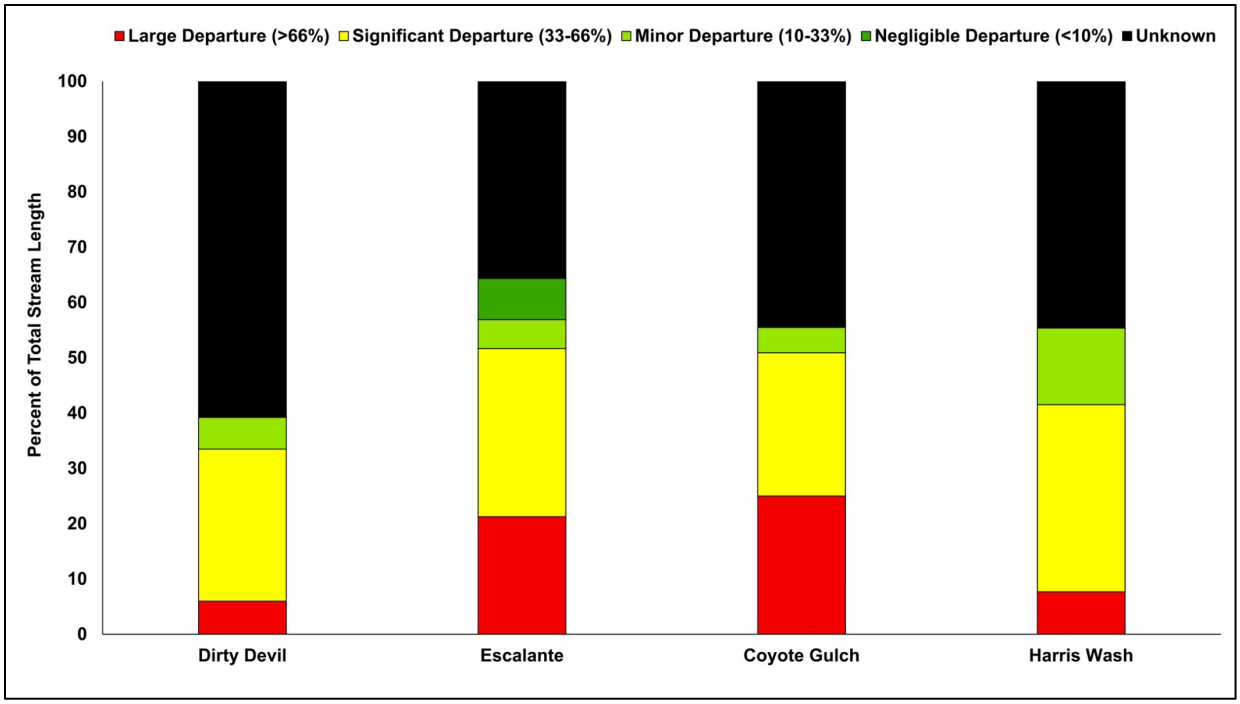


Figure 3.4.4-5. Percent of total stream length in each departure class for Dirty Devil, Escalante, Coyote Gulch, and Harris Wash.

Of the 170 plots located along the subset of streams, 15 contained at least one of the seven most problematic non-native species. These plots were located mostly in the upper Escalante River and Halls Creek. Surprisingly, none of the 170 plots sampled as part of the NPS vegetation mapping effort occurred within the riparian buffer zone along the Dirty Devil River. As a result, we could not assess the presence of invasive species using these data. However, both EPMT data and NPS vegetation mapping data show that Russian olive and tamarisk were mapped along a majority of the Dirty Devil River. From 2015 to 2017, 65 ha (160 ac) of Russian olive was treated in GLCA by the EPMT, the majority of which (64%) occurred along the Escalante River. The Escalante River

Watershed Partnership (ERWP; Spence and Whitman 2015), a multi-agency effort to restore riparian function on the Escalante River, considers the current condition of lowland riparian native versus non-native plants to be in poor condition (i.e., <50% non-native species) (ERWP 2015). But the ERWP and the NPS have removed Russian olive in all but 9.7 km (6 mi) of the Escalante River from its headwaters to its confluence with Lake Powell, including in GLCA (ERWP 2015). From 2009 to 2019, 111 ha (275 ac) of ravenna grass were treated in GLCA by the EPMT. Treatment areas did not occur in the subset streams included in this assessment. However, the EPMT mapped some areas of ravenna grass along the lower portion of the Escalante River and Lake Canyon as they were encountered. Based on these results, the condition of vegetation is poor. Confidence is medium because the data used to in each of the two measures did not occur in all of the riparian areas under consideration. Only about half of the subset streams were analyzed for departure from natural conditions and field data for non-native plants have not been collected regularly or systematically. A summary of conditions for all indicators is provided in Table 3.4.4-2.

Table 3.4.4-2. Riparian zone condition ratings summary.

Indicator	Condition Rating [1]	Trend	Condition Evaluation
Water Quantity and Availability	Fair	Deteriorating	Spring and summer discharge reveal a moderate departure from historical/reference criteria for the Escalante River but not for the Dirty Devil River. Non-native species comprise much of the riparian plants along some stream corridors, particularly the Dirty Devil River but vegetation has remained stable. Stream gage data were limited to two rivers and the others were estimated so confidence is medium.
Stream/ Watershed Health	Fair	Unknown	Since there were no impairments to water quality for the subset of streams analyzed, but some of the subwatersheds were rated as low or very low for aquatic intactness, the condition is fair. Confidence in the condition rating is medium because the measures were available for a single point in time and data availability and quality used to model aquatic intactness varied by subwatershed.
Vegetation	Poor	Unknown	Non-native species comprise much of the riparian plants along some stream corridors. Studies point to invasion by at least some of the seven most problematic invasive species and there are large patches along most of the subset streams. Confidence is medium because there are large spatial gaps in data coverage for the streams of interest.

[1] See Appendix B, Table B-2, for the 5-level condition rating statements for each indicator.

One concern pertaining to non-native species is determining which species are likely to invade as the climate changes, but predicting which species are likely to invade riparian areas in the coming decades is complicated by the fact that there is no current climate regime similar to future predicted climate for GLCA. Another concern regarding non-native species is the impact of nitrification on non-native plants. Increases in nitrogen deposition, coupled with grazing impacts to soils and

vegetation, promote invasions of fast growing nonnative annual grasses (e.g., cheatgrass) and forbs (e.g., Russian thistle) at the expense of native species (Brooks 2003; Schwinning et al. 2005; Allen et al. 2009). Russian olive, a nitrogen-fixing tree, may increase soil nitrogen by 55% (DeCant 2008). However, Katz et al. 2020 found that the additional nitrogen did not facilitate the colonization of invasive species in riparian areas. In recent years, the non-native desert willow (*Chilopsis linearis*), native to the Sonoran and Mojave Deserts, has appeared in some areas around Lake Powell and side canyons and is likely to spread further along intermittent streams (NPS GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, riparian review comment, Utah State University, 17 December 2020).

Stressors that impact the functioning of streams on the Colorado Plateau include warmer temperatures and increased drought, water withdrawals, and dewatering, lack of channel forming flows from scouring floods, shifts in precipitation intensity and timing, reduced snowpack, and presence of non-native invasive plants (Scott et al. 2005). Increased evapotranspiration by both native and non-native plants may also occur with warmer temperatures and longer summers. Of all the factors shaping riparian systems, precipitation amount and seasonality are the most important (Scott et al. 2005). While there was a slight increase in winter precipitation prior to 2000, there has been no increasing or decreasing trends in annual precipitation over the past 100 years. Mean annual temperatures have steadily increased (Spence and Cushing 2019), and there has been a persistent drought since 2000 (Lukas and Payton 2020). Although more severe droughts have occurred prior to 1900, anthropogenic climate change is likely to increase the recurrence interval of these "megadroughts" in the future (Lukas and Payton 2020). Warmer winters and earlier springs decrease the snowpack and bring more precipitation as rain, which alters the timing and amount of stream flows. In addition, more intense summer storms that drop large amounts of rain in very short time periods create larger flooding events that blowout riparian areas. All of these stressors can affect riparian ecosystems and will need to be monitored as the climate continues to change.

A warmer and drier climate may result in "terrestrialization" of the riparian zone, or conversion to facultative phreatophytes or upland plants (Scott et al. 2005), which will also be driven by water management decisions. In the Upper Colorado River Basin, 98% of water for agriculture and municipal use comes from surface water, while the remaining 2% comes from groundwater (Maupin et al. 2018). However, as surface water declines and the need for water grows, there is likely to be more pressure on aquifers (Maupin et al. 2018). While moderate water depletions may alter existing riparian plant composition and structure, severe water depletions will result in desertification (Scott et al. 2005). Channel incision and arroyo cutting in response to widespread and persistent grazing will also result in desertification/terrestrialization of the riparian zone (Scott et al. 2005).

Riparian vegetation composition and structure, channel morphology alterations, changes in stream flow, depth to groundwater, aquatic macroinvertebrate community, and water quality were identified as vital signs for monitoring riparian areas in the NPS SCPN (Thomas et al. 2006). These vital signs serve as drivers, stressors, and system components in the conceptual model of riparian areas for the SCPN (Appendix A-1 in Thomas et al. 2006). Although considered important to understanding riparian systems in the SCPN, none of these vital signs are currently monitored at Glen Canyon

NRA. However, monitoring and restoration efforts have and continue to occur along the entire length of the Escalante River as part of the ERWP (e.g., Scott et al. 2018).

3.5. Amphibians (Gap Analysis)

3.5.1. Background & Importance

Amphibians depend on access to fresh water for breeding and for the development of eggs, tadpoles, and froglets into their adult life stage (NatureServe 2020b). In GLCA, amphibians breed in slow-moving side channels, isolated pools, springs (Mueller et al. 1999), and tinajas, provided water persists throughout the breeding season and suitable overwintering terrestrial habitat is located nearby (Baron et al. 1998; Berghoff 1995). Water availability in streams and rivers depends on winter snowpack in the southern Utah and Colorado mountains north and east of GLCA, while tinajas (including waterpockets, ephemeral pools, and potholes) depend on local monsoon and intermittent rains (NPS 2014). Water discharged at springs and seeps is supplied by groundwater over days, weeks, or years (NPS 2014). Amphibians are a significant component of aquatic ecosystems, in addition to serving as indicators of water quality and wetland health (Stuart et al. 2004).

Plains spadefoot is unconfirmed at GLCA. Image Credit: NPS.

3.5.2. Status of Knowledge

NPSpecies (2020) currently lists 10 species of amphibian for GLCA, six of which are confirmed, three are unconfirmed, and one is probably present (Table 3.5.2-1). Nine species are listed as native,

but the American bullfrog (*Lithobates catesbeianus*), a non-native, was introduced to the western U.S. during the early to mid-1900s (Snow and Witmer 2010). Bullfrogs pose a significant threat to native amphibians because they are both predators and competitors of native species (Snow and Witmer 2010). However, the bullfrog has not yet been confirmed in GLCA based on specimens but has been heard calling in the lower Cataract Canyon above Hite, Utah by NPS staff (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mail, 2 October 2020).

Table 3.5.2-1. NPSpecies (2020) list of amphibians and observations of occurrence.

Species Name [1]	Common Name	NPSpecies Occurrence	Tanner (1958)	Mueller et al. (1999)	Nowak and Persons (2008)	AZGFD (2019)
Ambystoma tigrinum	Eastern Tiger Salamander	Present	X	–	–	–
Anaxyrus cognatus	Great Plains Toad	Unconfirmed	–	–	–	–
Anaxyrus punctatus	Red-spotted Toad	Present	X	–	X	X
Anaxyrus woodhousii	Woodhouse's Toad	Present	X	X	X	X
Hyla arenicolor	Canyon Treefrog	Present	X	–	X	X
Lithobates catesbeiana	American Bullfrog	Unconfirmed [2]	–	–	–	–
Lithobates pipiens	Northern Leopard Frog	Present	X	–	X	X
Spea bombifrons	Plains Spadefoot	Unconfirmed	–	–	–	–
Spea intermontana	Great Basin Spadefoot	Present	X	–	X	–
Spea multiplicata	Mexican Spadefoot	Probably Present	–	–	–	–

[1] Species names were updated to reflect current classification (SSAR 2020).

[2] NPS staff have heard bullfrogs calling in Cataract Canyon, but a specimen has not been collected.

According to species accounts in NatureServe (2020b), the amphibians listed for GLCA breed and develop in temporary or permanent pools with slow-moving or no flowing water. Non-breeding adults of all species except for American bullfrog and northern leopard frog aestivate underground, in rock crevices, or in other protective substrates. Both the American bullfrog and northern leopard frog require water year-round. The onset of summer monsoonal rains cues the start of the breeding season for most species, especially those that are terrestrial during the non-breeding season.

Tanner (1940, 1958) compiled GLCA's first checklist of herpetofauna based on his own observations and other incidental reports, which included the six species currently listed as present in NPSpecies. In June 1998, the Utah Department of Wildlife Resources (UDWR) surveyed amphibians at 13 stations along the Escalante River using daytime visual encounter and dusk call count surveys.

Woodhouse's toad occurred at 10 of the 13 stations (Mueller et al. 1999). Although the authors noted that Tanner (1940) reported Great Basin spadefoot, northern leopard frog, canyon treefrog, and red-spotted toad in the Escalante River drainage, these species were not observed during the 1998

surveys. Mueller et al. (1999) speculated that survey timing (late in the breeding season) and differences in behavior probably led to the lack of observations for other species.

In 2003, the NPS SCPN conducted the first comprehensive surveys for herpetofauna in GLCA using general diurnal and nocturnal surveys, night drives, and random encounters (Nowak and Persons 2008). Nowak and Persons (2008) documented five species in the field and one species from a museum specimen (Table 3.5.2-1). The authors estimated that their inventory, which included reptiles, was 76% complete based on a species accumulation curve but noted that two species, plains spadefoot (*Spea bombifrons*) and Mexican spadefoot (*Spea multiplicata*), are likely to occur in GLCA (Nowak and Persons 2008). Overall, at least one species was observed at 91% of the 131 survey stations that were located in wetlands, riparian areas, and hanging gardens.

Lastly, Arizona Game and Fish Department (AZGFD) biologists surveyed and collected northern leopard frogs in select areas of GLCA since 2006 (note that northern leopard frog is evaluated as a condition assessment separately due to more information than amphibians as a group). Although AZGFD's focus was on northern leopard frogs, other amphibians were recorded as encountered and one additional species was swabbed for *Batrachochytrium dendrobatidis* (*Bd*), a fungus that causes the infectious disease chytridiomycosis (hereafter referred to as chytrid disease). Collecting/survey trips occurred in April of 2006–2008, 2012–2015, and 2019 (AZGFD 2019). In addition to northern leopard frog, three other species were reported during these surveys: red-spotted toad, Woodhouse's toad, and canyon treefrog. A total of 66 northern leopard frogs and two canyon treefrogs were swabbed for *Bd* during these surveys but none tested positive.

In summary, amphibians were observed in six of GLCA's eight watersheds (Figure 3.5.2-1). No amphibians were reported for the Lower Green or Dirty Devil watersheds, but there was only one SCPN sampling site in the Dirty Devil and none in the Lower Green. Nor did other efforts include these areas. Furthermore, these areas represent a small fraction of GLCA and do not contain any major rivers. With the exception of the eastern tiger salamander (*Ambystoma tigrinum*), all species listed as present by NPSpecies were observed in the Escalante and Lower Lake Powell watersheds. However, GLCA staff have captured and positively identified both juvenile and adult eastern tiger salamanders in 2016–2018 and 2021 in an off-channel, spring-fed pond located 4.8 km (3 mi) downriver of Glen Canyon Dam. They were observed while removing non-native green sunfish (*Lepomis cyanellus*). For both the Paria and Lower Colorado-Marble Canyon watersheds, which represent a very small portion of GLCA, few amphibian species were reported.

Only the canyon treefrog was reported for the Lower San Juan Watershed, but park staff have commonly observed red-spotted toads and Woodhouse's toads in Wilson Creek and other side canyons on the San Juan arm (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mail, 2 October 2020). An amphibian survey in this watershed would provide additional baseline data, especially since evidence of breeding (e.g., egg masses, tadpoles, juveniles, mating pairs) was observed for Woodhouse's toad, Great Basin spadefoot, red-spotted toad, canyon treefrog, and northern leopard frog, although just beyond the park's boundary for the Great Basin spadefoot.

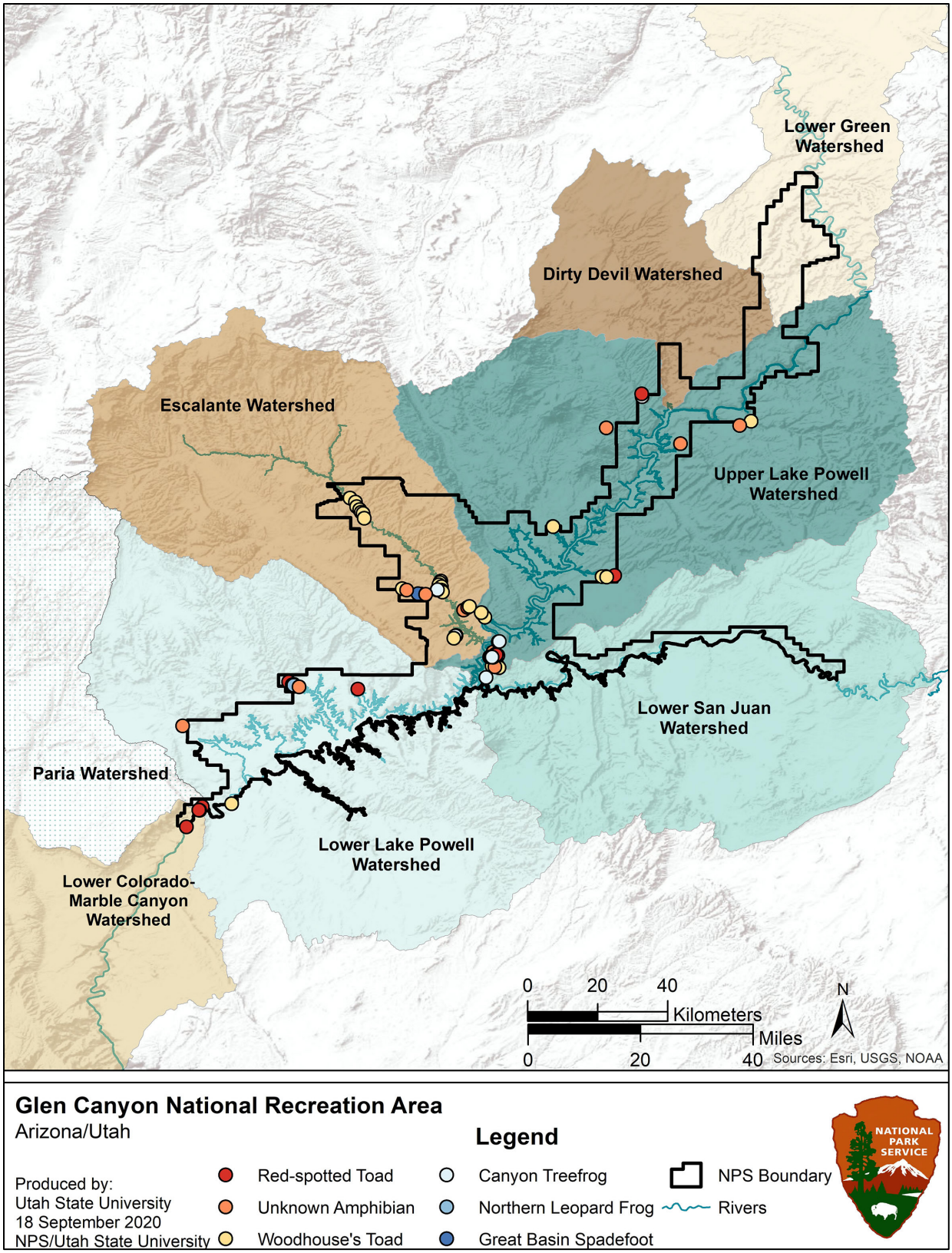


Figure 3.5.2-1. Locations of amphibians detected throughout GLCA.

3.5.3. Discussion

To facilitate a possible future condition assessment and/or study on amphibians in GLCA, we included a set of potential indicators and measures based on a conceptual model developed by the USGS Amphibian Research and Monitoring Initiative (ARMI) (Muths et al. 2006). The conceptual model is a three-tiered monitoring and research approach that includes general inventories at the base level; occupancy, general environmental data, species richness, and screening for potential causes of decline at the middle level; and population estimates, demographic studies, detailed environmental data, and long-term research at the apex level (Muths et al. 2006). Table 3.5.3-1 includes items from both the middle and apex levels of the conceptual model since a baseline inventory was done in 2003 (Nowak and Persons 2008).

Table 3.5.3-1. Proposed study details for amphibians.

Potential Indicator	Potential Measure	Potential Reference Criteria for Measure
Community Composition and Reproduction	Richness	Full complement of native species is represented across the range of suitable habitat. No loss in native species richness.
	Proportion of Sites Occupied	No declines in occupied sites.
	Proportion of Sites Where Breeding was Observed	No declines in breeding sites.
Water Quality	Core Water Quality Parameters	Water quality measures meet Utah/Arizona designated beneficial use requirements for wildlife and/or aquatic wildlife.
	Contaminants of Emerging Concern	Zero tolerance standard.
Non-native Species	Presence/Absence	Zero tolerance standard.
Disease	Presence/Absence	Zero tolerance standard.

Detection/non-detection data can be rapidly gathered, but because species are detectable at different times throughout the breeding season, multiple site visits may be necessary (Muths et al. 2006). Likewise, determining the proportion of sites with breeding activity (e.g., egg masses, tadpoles, juveniles, mating pairs) may also require multiple site visits in a given season. Patch or site occupancy has proven to be more informative than population size because patches are the unit at which most amphibian declines have been observed (Muths et al. 2006). Furthermore, detection/non-detection data are more easily gathered than population data. Detection/non-detection data can produce an "unbiased estimate of the proportion of sites occupied," which can be modeled using ARMI's PRESENCE software (Muths et al. 2006).

Reference criteria for the occupancy and breeding measures were unavailable for nearly all species that occur in GLCA (USGS 2020d). Rather than specific numerical criteria, we used reference criteria based on long-term data collection. Perhaps after baseline occupancy data are gathered, the reference criteria could be refined, but reference values are likely to vary by species since some amphibians are inherently more common than others.

Measures of core water quality (e.g., temperature, dissolved oxygen, pH) fall within general environmental data as described in Muths et al. (2006), while measures of contaminants of emerging concern, non-native species, and disease may help inform causes for declines in site occupancy, richness, and breeding, if declines are observed. Reference criteria for water quality measures were based on state standards for aquatic wildlife developed for Utah (UDWQ 2017) and Arizona (ADEQ 2020). Reference criteria for contaminants of emerging concern (e.g., pharmaceuticals and personal care products, flame retardants, pesticides, wastewater indicators) were based on a zero tolerance standard because water quality benchmarks for the majority of these substances have not been defined (Weissinger et al. 2018).

Similar to water quality, reference criteria for the presence of non-native species and diseases were also based on a zero tolerance standard because of the overwhelming evidence that these factors have caused widespread declines in amphibians across the U.S. (Muths et al. 2006). Chytrid disease has the potential to spread through humans and wildlife (e.g., birds), from one breeding pool to another (Johnson and Speare 2005). During AZGFD surveys, some areas contained non-native green sunfish, carp (*Cyprinus carpio*), bass (*Micropterus* spp.), bullhead (*Ameiurus* spp.), and mussels (*Dreissena* spp.) (AZGFD 2019). Of the 26 fish species in GLCA, 18 are non-native (NPSpecies 2020), and many prefer the slow-moving side channels and pools that native amphibians inhabit (Mueller et al. 1999).

Canyon treefrog. Image Credit: NPS.

Threats from airborne or atmospheric contaminants, such as heavy metals or nitrogen fertilizers warrant continued and perhaps more intensive monitoring of water quality, especially at breeding pools. More than 85,000 chemicals are of current commercial use in the U.S., half of which lack adequate toxicological studies for humans and the environment (Robichaud 2020). Semi-volatile organic compounds, including some persistent organic pollutants, and metals can and do travel substantial distances through the air, eventually settling into water and soils in more remote locations, including national parks (Landers et al.2010). Weissinger et al. (2018) found that during 2012 to 2016 at least one contaminant of emerging concern was found in water or sediments in eight

national parks, including GLCA. Atmospheric deposition of pollutants can then accumulate in amphibians and may contribute to population declines (Muths et al. 2006).

Grazing is permitted in GLCA but because there is not a park-wide amphibian habitat map, the extent to which grazing allotments overlap is unknown, although of the 192 springs mapped by the NPS, 32% are accessible to cattle, feral horses, and burros (NPS GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mailed park file to Lisa Baril, Utah State University, 18 December 2020). Thus, a key data gap is the absence of a habitat map, which was partially addressed by mapping tinajas and springs in this report. Existing sampling locations along streams and in wetlands surveyed by UDWR, AZGFD, and SCPN may serve as a framework for designing a sampling strategy, in addition to sightings within proximity to GLCA. For example, the plains leopard frog (*Lithobates blairi*) was confirmed by Charles Drost, research zoologist with USGS Southwest Biological Science Center, at the UDWR fish hatchery in Big Water, within a mile of the park's boundary (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mail, 2 October 2020), and the Arizona tiger salamander (*Ambystoma mavortium nebulosum*), confirmed by Larry Stevens, senior ecologist with the GCWC, was sighted 14.5 km (9 mi) upstream from Lees Ferry (Arizona Daily Sun 2020) at Leopard Frog marsh. Using a stratified random sampling design, occupancy data may also allow managers to detect range expansion, shifts in occupied versus unoccupied sites, and loss of species over time. More widespread surveys would also capture the effects of grazing on breeding sites.

Amphibians face a number of threats throughout their ranges, including disturbances such as flooding, fire, debris flow, grazing, introduced plants like ravenna grass, which is an emerging concern, bullfrogs, non-native crayfish, diseases, predatory fishes, loss of connectivity, loss of water resources (e.g., drought), miscues of behavior triggered by ORVs (Andrews et al. 2006), and other factors (Muths et al. 2006). Even native plants like *P. australis* have reduced the amount of open water habitat at some breeding pools (AZGFD 2019), but there does not appear to be one threat that outweighs all others. Rather, these threats work synergistically to affect individuals, populations, and communities (Collins and Storfer 2003; Muths et al. 2006). However, the threat of the loss of water resources is significant, particularly in arid environments like GLCA (Blaustein et al. 2010; Miller et al. 2018; Zylstra et al. 2015). The loss of water sources alone probably warrants additional monitoring and management of amphibians, irrespective of the many other threats to this resource.

3.6. Northern Leopard Frog (Condition Assessment)

3.6.1. Background & Importance

The northern leopard frog is a wide-ranging amphibian that occurs across the northern U.S. and Canada and south into Nevada, Arizona, and New Mexico (Smith and Keinath 2007). Over the last 60 years, the northern leopard frog has declined in many parts of its range for reasons that are not well understood (Smith and Keinath 2007). With permeable skin and dependence on wetlands, amphibians are particularly vulnerable to pollution of water resources and loss of wetlands, but introduced predatory fishes and disease are significant contributing factors in declines for this group (Muths et al. 2006; Smith and Keinath 2007). In 2006, the U.S. Fish and Wildlife Service (USFWS) was petitioned to list the northern leopard frog as threatened under the Endangered Species Act, but in 2011 the USFWS determined listing was not warranted (USFWS 2011). Thus, the northern leopard frog is managed at the state level. UDWR lists the northern leopard frog as a "species of greatest conservation need" (Utah WAP Joint Team 2015), and AZGFD lists this species as a high priority for management (AZGFD 2012). The northern leopard frog is considered uncommon in GLCA (NPSpecies 2020).

Northern leopard frog. Image Credit: © Douglas Wilhelm Harder.

3.6.2. Study Framework

We reviewed all available published reports (Craig and Pinnock 1995; Drost and Sogge 1995; Mueller et al. 1999; Nowak and Persons 2008; and Spence 1996b), unpublished reports (AZGFD 2019), and data files provided by GLCA staff (NPS GLCA, J. Spence, Deputy Chief of Natural

Resources & Chief Scientist, e-mailed park file to Lisa Baril, Utah State University, 18 December 2020) to determine the condition of four indicators for the northern leopard frog (Table 3.6.2-1). The indicators are occupancy, reproduction, and disease; the fourth indicator (plant encroachment) targets *P. australis*, which is an aggressive native reed that may reduce the amount of open water habitat in breeding pools (Mifsud 2014). However, due to the similar spectral signatures between *Phragmites* and other wetland plants (e.g., *Typha* spp.) (Maheu-Giroux and de Blois 2005), we assessed wetland plant cover more generally by mapping wetland plant cover in 1995 and 2017 at locations where northern leopard frogs currently occur and where they historically occurred when location information was available. We supplemented the mapping effort with information about *Phragmites* in known northern leopard frog locations using the abovementioned sources. Additionally, ravenna grass is also a non-native species known to occur in northern leopard frog habitat. Because this species if very difficult to control (Jackson 2015), it may impact northern leopard frog habitat if it increases. Given these concerns, we also surveyed the literature for where this species occurs in northern leopard frog locations in GLCA.

Table 3.6.2-1. Study details for the northern leopard frog condition assessment.

Indicator of Condition	Measure	Reference Criteria for Measure
Occupancy	Presence/Absence	Historically occupied sites are consistently occupied.
Reproduction	Evidence of Breeding	There is evidence of breeding activity at all sites surveyed, provided surveys were timed appropriately. Evidence includes egg masses, tadpoles, and mating pairs.
Disease	Presence/Absence	None detected or very low prevalence.
Plant Encroachment	Cover	Little to no invasion of *Phragmites* or ravenna grass in known northern leopard frog breeding habitat.

There are spatial and temporal data gaps in northern leopard frog data (i.e., some years and/or places were not surveyed), but the majority of survey dates range from 1992 to 2019. Most surveys occurred in the Escalante, Upper Lake Powell, and Lower Lake Powell watersheds. The measures and reference criteria are based on the available data and key attributes considered important to assessing condition of the selected indicators (Muths et al. 2006).

3.6.3. Data & Methods

Based on information included in the reports listed above, we mapped all areas where leopard frogs currently occur, where they've been extirpated, and where they've been observed in the past, but the current status is unknown. In June 1998, the UDWR surveyed amphibians at 13 stations along the Escalante River using daytime visual encounter and dusk call count surveys (Mueller et al. 1999). In 2003, the NPS SCPN conducted the first comprehensive surveys for herpetofauna in GLCA using general diurnal and nocturnal surveys, night drives, and random encounters (Nowak and Persons 2008). In 2008, AZGFD biologists collected northern leopard frog tissue samples for a genetics study (O'Donnell and Mock 2008). Lastly, AZGFD biologists have surveyed for and collected northern

leopard frogs in select areas of GLCA since 2006 (note that amphibians as a group are evaluated in a gap analysis due to the absence of information for other species).

A total of 74 northern leopard frogs, four canyon treefrogs and one Woodhouse's toad were swabbed for *Bd*, the fungus that causes chytridiomycosis, from 2007 to 2019 in four drainages: Ribbon Canyon, Bowns Canyon, Davis Gulch and an unnamed drainage across from Pollywog Bench (hereafter referred to as Unnamed Drainage). Other data included monitoring reports of the population at Horseshoe Bend (Craig and Pinnock 1995; Drost and Sogge 1995; Spence 1996b) and references to earlier observations of northern leopard frog sites in GLCA (Drost and Sogge 1995; Tanner 1940).

Evidence of breeding (e.g., egg masses, tadpoles, juveniles, mating pairs) was summarized by location and year-based information in the abovementioned reports and databases. Because occupied sites were not surveyed consistently over time, we pooled data for all sites and all years to determine the proportion of sites for which breeding was observed. These pooled site-year combinations allowed for a general sense of total breeding occurrence since surveys began, but we could not determine trend over time due to limited annual data. However, because AZGFD conducted annual surveys at four locations, we also subset breeding data to include only those sites consistently surveyed from 2006 to 2019 (AZGFD 2019).

For the plant encroachment indicator, there were 11 leopard frog areas for which specific location data were available. For locations with multiple survey points along a stream, we created a 200 m (656 ft) buffer along the NHD's stream polyline for those locations (USGS 2020b), ensuring that all points and visible wetland plants were included in the buffer area. For single-point locations, we created a polygon that included visible wetland vegetation within 200 m to 400 m (656–1,312 ft) of the point depending on the size of the wetland. We confirmed that wetland vegetation was included in the buffer areas using 2018, 1-m (3.3-ft) natural color aerial photos obtained from NAIP (USDA 2020a).

To determine change in cover over time, we used maximum normalized difference vegetation index ($NDVI_{max}$) raster files created by the NASA DEVELOP Glen Canyon Eco Team (Frier et al. 2018). $NDVI_{max}$ raster files were available from 1995 to 2017 and were derived from Landsat satellite imagery with a resolution of 30 m (98 ft). After clipping the 1995 and 2017 raster files to the 11 analysis locations, we used the raster calculator function in ArcGIS 10.1 to separate wetland vegetation from non-wetland areas. We considered $NDVI_{max}$ pixel values of ≥ 0.4 as wetland vegetation based on a visual comparison between $NDVI_{max}$ pixel values and NAIP imagery. We then calculated the percent of wetland vegetation in each location in 1995 and 2017. We used a paired t-test to determine if the change between the two periods was significant ($\alpha = 0.05$).

3.6.4. Results & Discussion

Prior to the completion of Glen Canyon Dam in 1966, northern leopard frogs were known to occur in at least 15 locations along the Colorado River and side tributaries above where the dam was eventually constructed (Drost and Sogge 1995; Tanner 1940; Figure 3.6.4-1). Following completion of the dam, 14 of these sites were flooded by Lake Powell (Drost and Sogge 1995; Tanner 1940).

Drost and Sogge (1995) were uncertain of the status of the remaining site; however, no leopard frogs were observed there during a reconnaissance survey in 2007 (AZGFD 2019). The elimination of leopard frog habitat along the Colorado River mainstem effectively isolated

populations in side canyons (Drost and Sogge 1995; O'Donnell and Mock 2008). A study of the genetic diversity of northern leopard frogs in GLCA and adjacent Canyonlands NP revealed pronounced genetic differences between populations, and low genetic diversity and inbreeding within populations (O'Donnell and Mock 2008).

From the late 1970s to the early 1990s, there were three intensive multiyear studies along the river corridor, but no other leopard frog populations were documented during these efforts (Drost and Sogge 1995). In 1992, NPS staff found a population at Horseshoe Bend on the Colorado River (Drost and Sogge 1995). The discovery prompted surveys of the Horseshoe Bend site and other suitable habitat along the Colorado River from the dam to Lees Ferry, as well as suitable tributary canyons of Lake Powell, but leopard frogs were found at only three of the 14 sites surveyed: Horseshoe Bend, Bowns Canyon, and Ribbon Canyon (Drost and Sogge 1995).

From 1992 to 2003, NPS staff documented northern leopard frogs encountered while surveying springs, seeps, and hanging gardens along tributary streams and side canyons (NPS GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mailed park file to Lisa Baril, Utah State University, 18 December 2020). In 1993, the same year of the Drost and Sogge (1995) survey, there were five additional sites occupied by northern leopard frogs. By 2003, NPS staff had documented 11 distinct populations, two of which had been extirpated or were near extirpation. These sites were Horseshoe Bend, where only one adult frog (and egg mass) was observed in 2004 (Drost et al. 2008 as cited in Stortz et al. 2018; Drost et al. 2011), and Lower Wilson Creek, which was extirpated by 1995 (NPS GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mailed park file to Lisa Baril, Utah State University, 18 December 2020).

In 1998, Mueller et al. (1999) surveyed 13 locations along the Escalante River but did not encounter northern leopard frogs. During the 2003 SCPN inventory, 24 northern leopard frogs were reported (12 adults and 12 subadults/immatures). Four individuals were randomly encountered and 20 were reported during general surveys. Most frogs (17) were observed in Ribbon Canyon, but a few were also observed in Explorer Canyon and Last Chance Creek. Frogs were not observed in the 15 other areas surveyed for amphibians; however, some or several of these sites may not have been suitable habitat for northern leopard frogs.

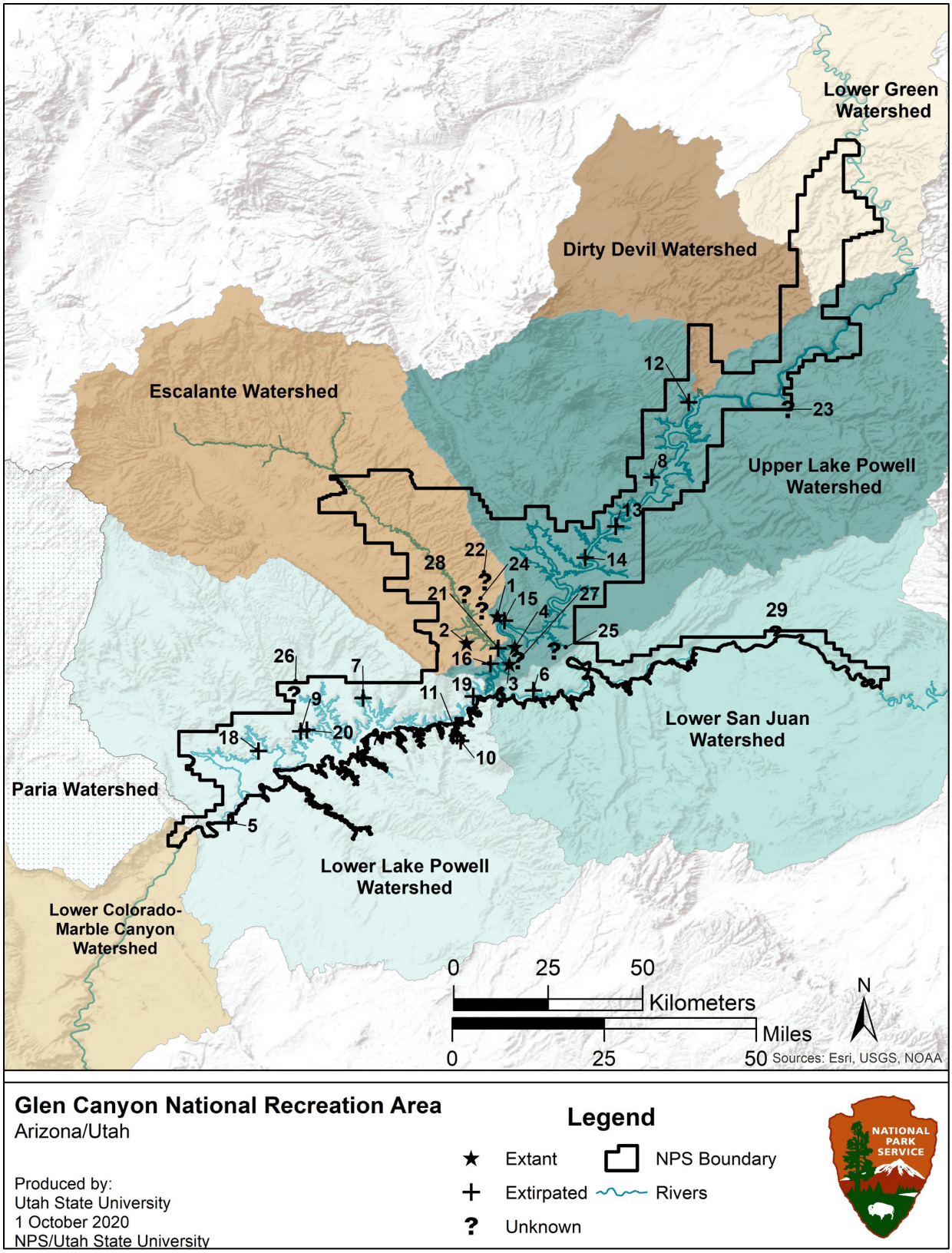


Figure 3.6.4-1. Extant, extirpated, and unknown status site locations for northern leopard frog populations.

O'Donnell and Mock (2008) collected tissue samples from frogs at Davis Gulch, Bowns Canyon, Ribbon Canyon, and Unnamed Drainage across from Pollywog Bench. These were all known locations, but they also collected samples from frogs at Grand Gulch of the San Juan Arm, which was a site not reported in any of the other surveys. No specific location information was available for this site. Finally, AZGFD surveyed for northern leopard frogs consistently at four locations from 2006 to 2019. Leopard frogs were observed each year in which a site was surveyed. Sites were surveyed for northern leopard frogs in 2007 at historically occupied sites (Rainbow Bridge, Rock Creek, and West Canyon Creek) and at two locations with potential habitat (Dry Rock Creek, Forbidding Canyon), but no frogs were observed at any of these locations (AZGFD 2019).

In summary, northern leopard frogs have occurred in or currently occur in 29 locations in GLCA, 17 of which are now extirpated (Table 3.6.4-1). The status for the remaining eight locations is unknown since the last observations occurred sometime between 1992 and 2003 (NPS GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mailed park file to Lisa Baril, Utah State University, 18 December 2020; Nowak and Persons 2008). This represents a loss of 81% of all known locations since about the mid-1950s (i.e., 17 of 21 areas extirpated). Based on the reference criteria statements for the occupancy indicator, the condition is poor. Although surveys were not systematic or widespread, the accumulation of data shows a substantial decline in occupied areas over the last 70 years. Confidence in the condition rating is high due to the overwhelming evidence accumulated for GLCA from the various studies.

Table 3.6.4-1. Summary of extant, extirpated, and unknown status for northern leopard frogs by location.

Map Number	Site Name	Status	Years of Confirmed Occupancy	Years of Confirmed Breeding
1	Bowns Canyon	Extant	1992, 1993, 1994, 2003, 2005, 2006, 2007, 2012, 2014, 2015, 2019	1993, 2006, 2012, 2014, 2015, 2019
2	Davis Gulch	Extant	2003, 2006, 2008, 2012–2014	2012, 2013, 2014
3	Ribbon Canyon	Extant	1992, 1993, 1994, 2003, 2006, 2007, 2008, 2012–2015, 2019	1992, 1993, 2006, 2007, 2008, 2012, 2013, 2014, 2015
4	Unnamed Drainage Across from Pollywog Bench	Extant	1994, 2003, 2005, 2006, 2007, 2014, 2015	1994, 2003, 2006, 2014, 2015
5	Horseshoe Bend	Extirpated	1992–2004	1993, 1995, 1996, 2004
6	Lower Wilson Creek	Extirpated	1992, 1994	No Breeding Observed
7	Rock Creek	Extirpated	Pre-dam; checked in 2007	–
8	Below Mouth of Ticaboo Creek	Extirpated	Pre-dam	–

[1] NPS staff have observed frogs in the West Fork of Iceberg Canyon through about 2015 (and possibly more recently); they are likely still present (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, comments on draft, 14 October 2020).

[2] Site is probably connected to Ribbon Canyon.

Table 3.6.4-1 (continued). Summary of extant, extirpated, and unknown status for northern leopard frogs by location.

Map Number	Site Name	Status	Years of Confirmed Occupancy	Years of Confirmed Breeding
9	Padre Creek	Extirpated	Pre-dam	–
10	Above Rainbow Bridge	Extirpated	Pre-dam; checked in 2007	–
11	Below Rainbow Bridge	Extirpated	Pre-dam; checked in 2007	–
12	Lower Trachyte Creek	Extirpated	Pre-dam	–
13	River Mile 109	Extirpated	Pre-dam	–
14	River Mile 101.5	Extirpated	Pre-dam	–
15	Lower Long Canyon	Extirpated	Pre-dam	–
16	Hole-in-the-Rock	Extirpated	Pre-dam	–
17	West Canyon Creek	Extirpated	Pre-dam; checked in 2007	–
18	Warm Creek	Extirpated	Pre-dam	–
19	Hidden Passage	Extirpated	Pre-dam	–
20	Lower Kane	Extirpated	Pre-dam	–
21	Mouth of Escalante River	Extirpated	Pre-dam	–
22	Cow Canyon	Unknown	1992	No Breeding Observed
23	Dark Canyon	Unknown	2003	No Breeding Observed
24	Explorer Canyon	Unknown	1995, 2003, 2005	1995
25	Iceberg Canyon	Unknown	1995	No Breeding Observed
26 [1]	Last Chance Creek	Unknown	2003	–
27 [2]	North Fork Ribbon Canyon	Unknown	1992	No Breeding Observed
28	Rose Canyon	Unknown	1993, 1995	No Breeding Observed
29	Grand Gulch	Unknown	2006	–

[1] NPS staff have observed frogs in the West Fork of Iceberg Canyon through about 2015 (and possibly more recently); they are likely still present (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, comments on draft, 14 October 2020).

[2] Site is probably connected to Ribbon Canyon.

None of the 79 samples tested for *Bd* were positive. Thus, the condition for this indicator is good. Because these data are recent, occurred over several years, and samples were collected in all four extant populations, confidence in the condition rating is high and trend is stable.

We mapped change in NDVI*max* for 11 locations (4 extant, 2 extirpated, and 5 unknown status). There was a 385% increase in wetland cover from 1995 to 2017 (t (10) = −2.8, $p < 0.05$). None of the 11 sites declined in wetland cover, but three sites did not exhibit any changes because riparian/wetland vegetation was not mapped in either year (Figure 3.6.4-2). Davis Gulch exhibited the largest increase while Ribbon Canyon exhibited the least change. For the three sites that did not change, wetland cover was not mapped in either year. A major challenge with mapping vegetation in GLCA is the steep topography of side canyons that may obscure wetland plants through shadows,

rock walls, and outcroppings (Davis et al. 2002). Although we could not distinguish between *Phragmites* and other wetland plants, this species is present in many of the locations mapped.

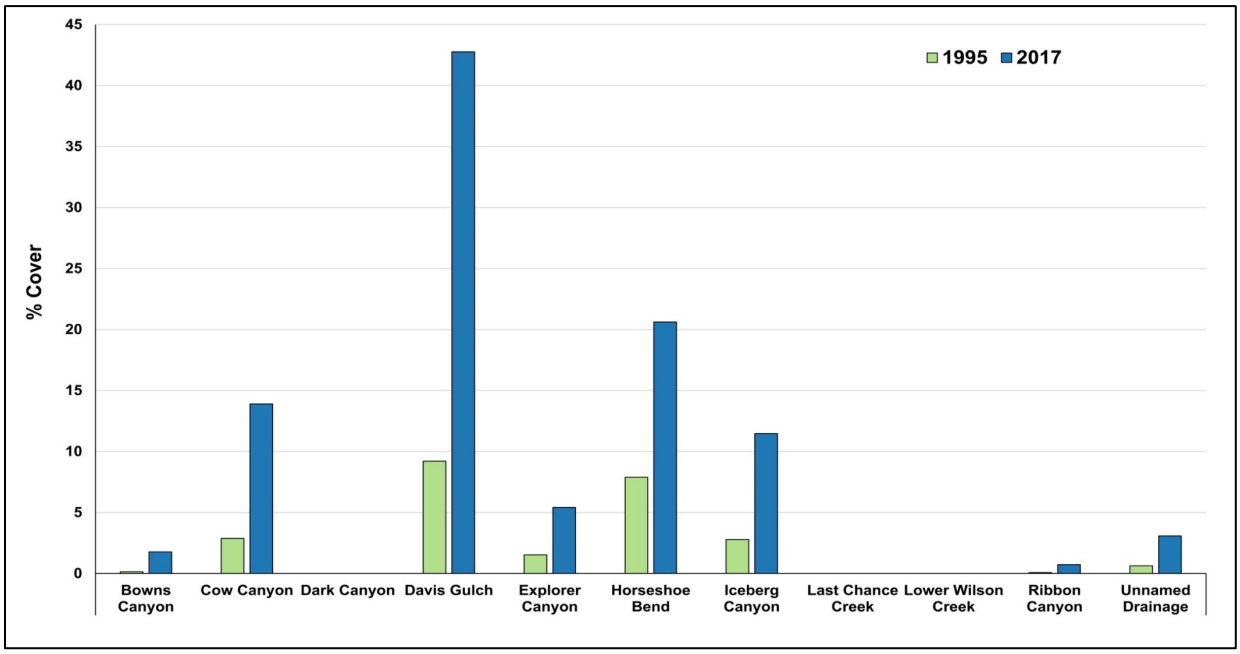


Figure 3.6.4-2. Percent cover of wetland vegetation during 1995 and 2017 at 11 northern leopard frog locations.

During AZGFD's survey trips, observers noted *Phragmites* in Davis Gulch and Ribbon Canyon. At Davis Gulch *Phragmites* apparently increased substantially between the 2009 visit and the 2012 visit. The authors noted that the Davis Gulch wetland was extensive with many calling frogs in 2009 but by 2012 was "choked and drying out with *Phragmites*" (AZGFD 2019). In October 2002, Davis Gulch had undergone major changes due to a flood the previous October resulting in large cutbanks, uprooted cottonwoods (*Populus* spp.), and flood debris (AZGFD 2019). The increase in *Phragmites* might have been the result of this disturbance.

This is supported by a study of riparian plants along the Colorado River below the dam following a controlled flood in 2008 (Ralston 2010). The author found that *Phragmites* increased from 0.5% in April (pre-flood) to 1.5% in September (post-flood), but the increase was not statistically significant (Ralston 2010). The removal of fine-grained sediments appears to favor clonal species like *Phragmites* (Ralston 2010). According to GLCA's springs database, *Phragmites* is also present in Bowns Canyon, Horseshoe Bend, and Rose Canyon (NPS GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mailed park file to Lisa Baril, Utah State University, 18 December 2020). Craig and Pinnock (1995) mapped *Phragmites* over a large area at Horseshoe Bend in 1995 and Spence (1996a) found that *Phragmites* increased between 1995 and 1996 at this site. Gloss et al. (2005) reported that the main breeding pool at Horseshoe Bend had completely filled in with *Phragmites* because of the 1996 decision to reduce flows through Glen Canyon Dam. Highly variable flows maintain open breeding pools, but when flow variability was reduced, formerly open habitat

was filled in with *Phragmites* (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, comments on draft, 14 October 2020). Mueller et al. (1999) reported that *Phragmites* was common along the Escalante River as well. Ravenna grass is also present in Bowns and Ribbon canyons (AZGFD 2019). Cheatgrass or other *Bromus* species were also observed in Davis Gulch.

While we could not fully assess the condition of *Phragmites* encroachment, there has been a significant increase in wetland plant cover in known northern leopard frog locations, especially in extant sites. At least some of this cover is *Phragmites* given the information provided in the various sources cited above. For these reasons, the condition is poor, but confidence in this condition is low because we could not specifically address *Phragmites* cover. A summary indicators, condition, and rationale is provided in Table 3.6.4-2.

Table 3.6.4-2. Northern leopard frog condition ratings* summary.

Indicator	Condition Rating	Trend	Condition Evaluation
Occupancy	Poor	Deteriorating	Although northern leopard frog surveys were not generally systematic over time, the accumulation of data indicates a decline in occupied areas, with a deteriorating trend. Confidence in the condition rating is high due to the overwhelming evidence accumulated for GLCA.
Reproduction	Good	Stable	Where northern leopard frogs are found, evidence of breeding has always been observed. Confidence in the condition rating is low due to the small sample size.
Disease	Good	Stable	A total of 74 northern leopard frogs were tested for *Bd* in Ribbon Canyon, Davis Gulch, Bowns Canyon, and Unnamed Drainage across from Pollywog Bench (2007–2019) and no frogs tested positive. Confidence in the condition rating is high because sampling is current and occurred in all four extant populations.
Plant Encroachment	Poor	Deteriorating	There has been a significant increase in wetland plant cover in known northern leopard frog locations, especially in extant sites. At least some of this cover is *Phragmites* given the information provided in the various sources cited. However, confidence in this condition is low because we could not directly evaluate cover.

* See Appendix B, Table B-3, for the 5-level condition rating statements for each indicator.

The potential loss of water sources probably warrants additional monitoring and management actions for amphibians as a whole, and northern leopard frogs in particular. This group is dependent on water resources for breeding. Loss of breeding pools had already occurred with the creation of Lake Powell, which eliminated breeding habitat and isolated populations in side canyons and tributaries to the lake. Other factors that reduce water resources include *Phragmites* and ravenna grass encroachment, climate change such as the 1998–2021 drought that has affected baseflows in streams such as Davis Gulch, and disturbances like flooding, grazing, and perhaps backcountry use.

Non-native predatory fishes and aquatic invertebrates are also a major threat to amphibians (Muths et al. 2006). AZGFD (2019) reported several non-native species during their surveys. At Ribbon Canyon, they reported green sunfish, carp, crayfish, and quagga mussels (*Dreissena rostriformis*) and at Davis Gulch they reported green sunfish, bass, bullhead, and crayfish.

Of the four extant northern leopard frog sites, three are located in an active grazing allotment, but none are accessible to cattle due to sheer cliff walls (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, comments on draft, 14 October 2020). Bowns Canyon is the only site outside of a grazing allotment, but this site is also inaccessible to cattle (CBI 2020). Although northern leopard frogs are known to occur in only a handful of springs or pools below hanging gardens, of the 192 springs mapped by the NPS, 32% are accessible to cattle (NPS GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, e-mailed park file to Lisa Baril, Utah State University, 18 December 2020). This could be a factor in the loss or absence of frogs in certain sites.

Similar to amphibians as a group, threats from airborne or atmospheric contaminants, such as heavy metals or nitrogen fertilizers, warrant continued and perhaps more intensive monitoring of water quality, especially at breeding pools (refer to section 3.5.3 for additional information). Some persistent organic pollutants and metals can travel substantial distances through the air, eventually settling into water and soils in more remote locations, including national parks (Landers et al.2010), and these can then accumulate in amphibians and may contribute to population declines (Muths et al. 2006).

The most significant data gap for the northern leopard frog is the absence of follow-up surveys at the eight sites of unknown status. Although the purpose of AZGFD's surveys was to collect eggs for reintroduction elsewhere, perhaps additional data could be collected at these locations, such as estimates of *Phragmites* cover. Habitat surveys in general of known locations would be valuable as would establishing a protocol so that robust occupancy estimates can be determined (Muths et al. 2006). Although *Bd* does not appear to be a factor in northern leopard frog declines, other diseases such as *Ranavirus*, could be present. Disease and malformations are major factors in amphibian declines elsewhere, but baseline data are lacking (Muths et al. 2006).

Muths et al. (2006) developed a conceptual model for monitoring amphibian populations. The three-tiered monitoring and research approach includes general inventories at the base level; occupancy, general environmental data, species richness, and screening for potential causes of decline at the middle level; and population estimates, demographic studies, detailed environmental data, and long-term research at the apex level (Muths et al. 2006). Implementing some or all of these levels in a systematic way at GLCA would help managers understand northern leopard frog declines and perhaps lead to management actions that would increase occupancy.

Currently, NPS, AZGFD, and GCWC are working on re-introduction of northern leopard frogs at Horseshoe Bend. Breeding pools have been created and re-introduction efforts will likely start in 2022 (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, comments on draft, 14 October 2020).

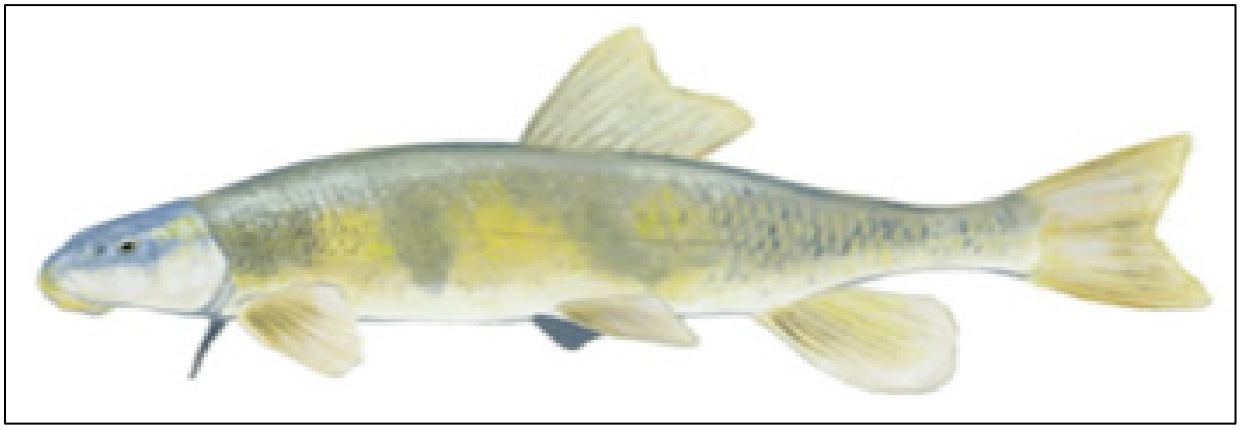
3.7. Fishes (Condition Assessment & Gap Analysis)

3.7.1. Background & Importance

Of the 26 fish species in GLCA, 18 are non-native (NPSpecies 2020). While most non-native fishes are common or abundant, all but one native species (speckled dace) are rare (NPSpecies 2020). Of the eight native species found in the park, four are listed by the USFWS as federally endangered (NPS 2020b). These are the razorback sucker (*Xyrauchen texanus*), humpback chub (*Gila cypha*), bonytail chub (*Gila elegans*), and Colorado pikeminnow (*Ptychocheilus lucius*). Two of these species, razorback sucker and humpback chub, are currently under review (starting in 2019) for downlisting from endangered to threatened status by the USFWS (USFWS 2018).

Of the four remaining native species (bluehead sucker (*Catostomus discobolus*), flannelmouth sucker (C. *latipinnis*), roundtail chub (*Gila robusta*), and speckled dace), none are listed as threatened or endangered, but three (bluehead sucker, flannelmouth sucker, and roundtail chub) are in decline in Utah (UDWR 2006). Because all four species are not sportfish nor fall under federal protection, they are less well studied than other fishes in the region and were selected as the species of interest for this combined condition assessment/gap analysis.

In an effort to prevent the listing of the bluehead and flannelmouth suckers and roundtail chub as threatened or endangered in the future, the UDWR published a conservation and management plan focused on these three under-studied fishes (UDWR 2006) as part of a larger effort among the four states in which they occur (Wyoming, Arizona, Colorado, and Utah). However, it's important to note that both sucker populations below the Paria River and throughout the Grand Canyon have experienced a recent rebound and are considered to have healthy populations (Walters et al. 2012).



In the early 2000s, the bluehead sucker was believed to be restricted to approximately 50% of its historic range. Illustration Credit: UDWR/Ben Sutter.

3.7.2. Study Framework

Table 3.7.2-1 includes the four indicators of condition (water quantity and availability, water quality, biological (fish) community, and habitat quality and availability) used to assess the bluehead sucker, flannelmouth sucker, roundtail chub, and speckled dace in the four largest tributaries of the Colorado River: Escalante, Paria, San Juan, and Dirty Devil (Figure 3.7.2-1). Although we included 10

measures across four indicators, we were unable to evaluate all measures for each river or fish species due to lack of data. As a result, this assessment is a hybrid between a condition assessment and a gap analysis. Water quantity and availability data and water quality data were available for all four streams. However, benthic macroinvertebrate data were limited to the Escalante River. Measures of the biological (fish) community and habitat quality and availability were available for the Escalante River and San Juan rivers, but not for the Paria or Dirty Devil rivers. Although there have been fish surveys in these streams, we are aware of only one that occurred in GLCA (McIvor and Thieme 1999).

Table 3.7.2-1. Study details for the fishes condition assessment.

Indicator of Condition	**Measure**	**Reference Criteria for Measure**
Water Quantity and Availability	Flow Variability	Flow variability mimics historic patterns, particularly during spring.
Water Quality	Core Parameters (dissolved oxygen, sulfate, maximum temperature, pH, *E. coli*, total dissolved solids)	Fewer than 10% of samples exceed the criteria for supported uses (must meet minimum sample size of 10/site).
	Toxic Parameters (hardness, aluminum, ammonia, fluoride, hydrogen sulfide, boron)	Fewer than two exceedances of acute and/or chronic criteria (must meet minimum sample size of 4/site).
	River Invertebrate Prediction and Classification System Ratio for Benthic Macroinvertebrates	Mean observed/expected score ≥ 0.76 for < 3 samples or ≥ 1 sample collected over 8 years.
Biological Community	Native Fish Occurrence	All four species are consistently present in each of the surveys conducted.
	Frequency of Individuals by Length	Length-frequency histograms indicate a stable or growing population with multiple age classes represented.
	Non-native Fish Occurrence	Non-native species are absent or limited in distribution and abundance.
	Non-fish Aquatic Invasive Species Occurrence	Non-native species are absent or limited in distribution and abundance.
Habitat Quality and Availability	Bedform (e.g., cobble bar or shoal)	Distribution and amount of bedform types reflect suitable habitat conditions.
	Hydraulic Feature (e.g., eddy, riffle, run)	Distribution and degree of hydraulic features reflect suitable habitat conditions.

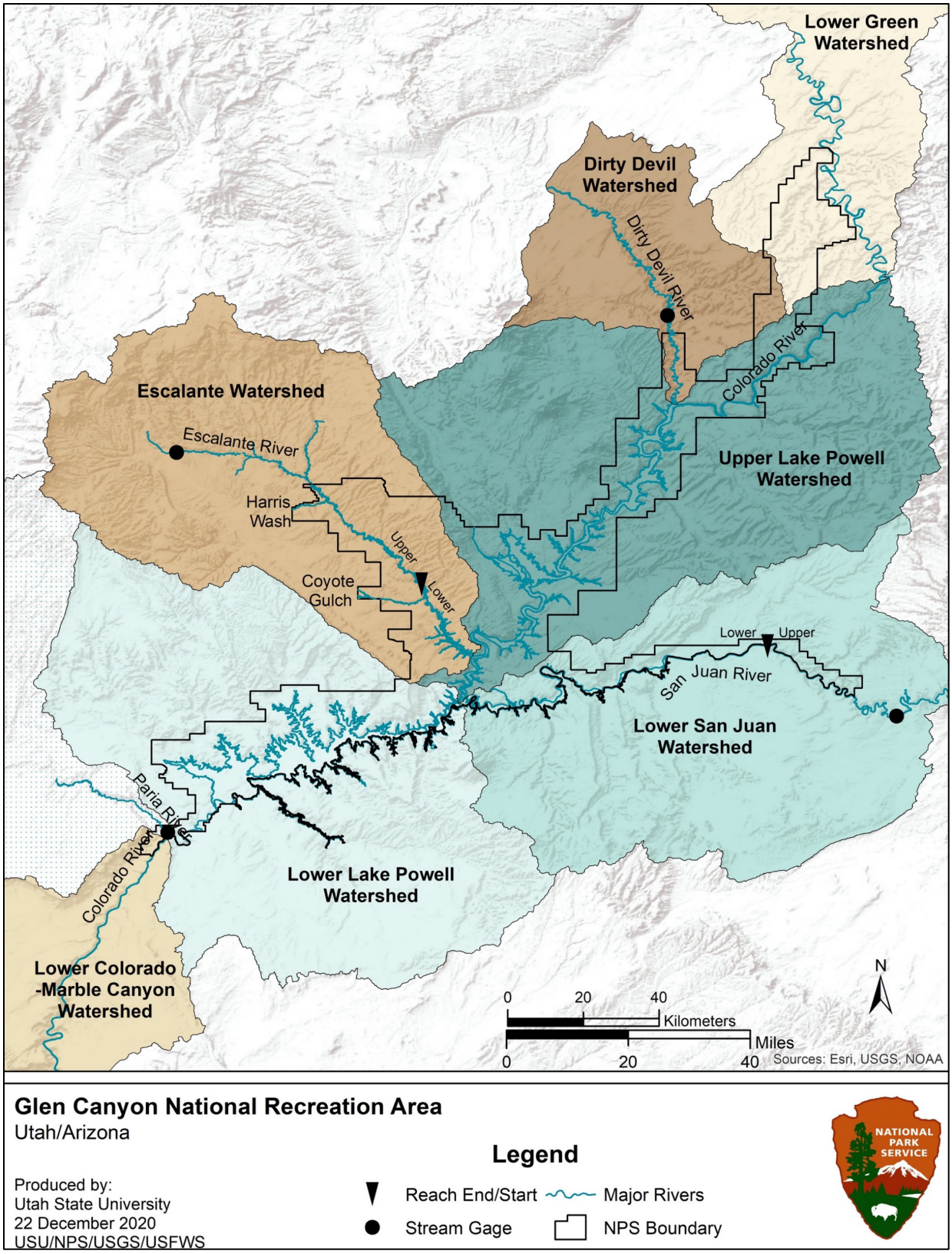
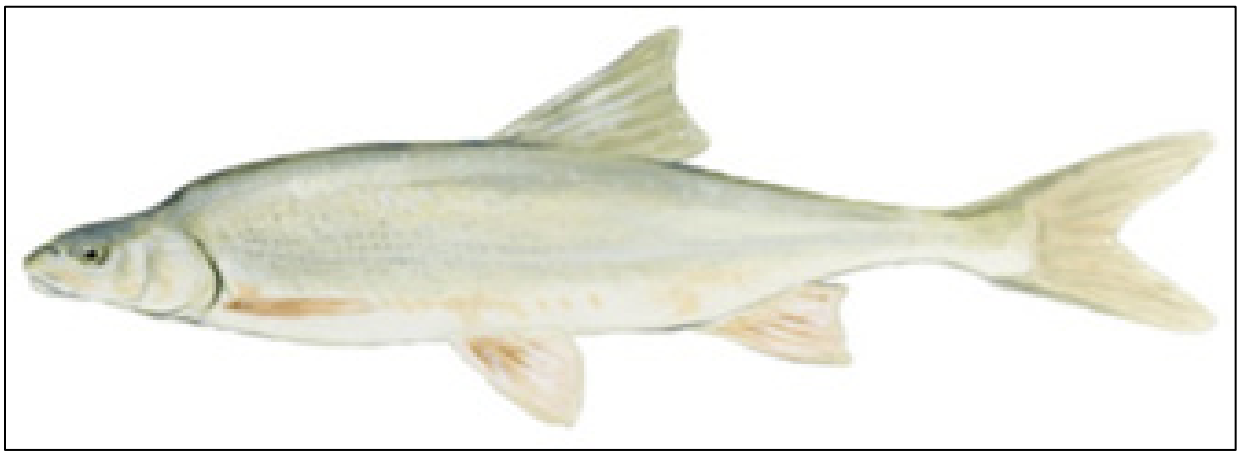


Figure 3.7.2-1. Locations of study areas for fishes.

Reference criteria for water quantity and availability were derived from Holden (1999), which states that natural hydrologic regimes create the conditions to support native fish populations, and mimicry of the natural hydrograph is the foundation for good condition. Measures and reference criteria for water quality were derived from the UDWQ (2017, 2020) and the AWQD (2017, 2018) guidance for warm water wildlife. The reference criteria for measures of the biological community are based on the overwhelming evidence that non-native species cause harm to native fish communities and that intact native communities can signal ecosystem health. Specifically, reference criteria for native fish recruitment and habitat measures were derived from UDWR (2009) and Woodhouse and Fridell (2017). Numerical criteria were not given since the four species differ in their growth and development patterns. Similarly, the four species rely on different habitat characteristics depending on life stage. Furthermore, there is variability in habitat preferences between species (Bezzerides and Bestgen 2002; Bower and Hubert 2008; Holden 1999). Therefore, we characterized habitat more generally based on the available information (Lamarra and Lamarra 2018; Woodhouse and Fridell 2017).



The roundtail chub occupied only 18% to 45% of its historic range in the 2000s. Illustration Credit: UDWR/Ben Sutter.

3.7.3. Data & Methods

The Bureau of Reclamation has developed natural flow models for 29 gaged USGS stream stations in the Upper Colorado River Basin, two of which are relevant to this assessment: San Juan River near Bluff, Utah (USGS ID: 09379500) and the Paria River at Lees Ferry, Arizona (USGS ID: 09382000) (Bureau of Reclamation 2020). For these two locations, we determined the difference between natural estimates of stream flow (1906–2018) to observed flow data, which were available for the San Juan River from 1929 to 2018 and the Paria River from 1924 to 2018 (USGS 2020c). In addition to departure from total natural flow, we also looked for departure of the natural flow pattern from April to October. We used April through October to capture peak floods and the return to base flows.

Although the Bureau of Reclamation estimates of natural flows were not available for the Dirty Devil (USGS ID: 09333500) or Escalante (USGS ID: 09337500) stream gage sites, Laub et al. (2018) identified historical (or reference) ranges that occurred prior to large-scale water development. The

reference period for the Dirty Devil River included a 10-year period from 1948 to 1957, and the historical period for the Escalante River spanned a 13-year period from 1943 to 1955 (Laub et al. 2018). We compared USGS discharge data for the historical range to the most recent (2008–2019) ranges available for April to October and to total annual flow (USGS 2020c).

Core water quality and toxic parameter data were downloaded from UDWQ (2017, 2020) and AWQD (2017, 2018) websites. We included impairment statistics for the most recent monitoring cycle (2018 and 2020) as well as data for the previous monitoring cycle (2014 and 2016). Stream impairment data for the current monitoring cycle (i.e., 2020) in Utah are provisional and subject to change (UDWQ 2020). The NPS SCPN also monitors core water quality, toxic parameters, and contaminants of emerging concern at two locations along the Escalante River (above and below Coyote Gulch) (Dyer et al. 2016, 2017). Data for these two sites were available from 2011 to 2014 (Dyer et al. 2016, 2017).

The flannelmouth sucker is believed to occupy approximately 45% of its historic range. Illustration Credit: UDWR/Ben Sutter.

The River Invertebrate Prediction and Classification System (RIVPACS) ratio listed in Table 3.7.2-1 is an approach used by Utah's DWQ, and is based on a comparison of an observed score to an expected score at a reference site (Miller and Judson 2011). RIVPACS ratios were not available for the river reaches under consideration in this assessment but may be available for future application to SCPN parks (Brasher et al. 2011). Instead, we summarized aquatic macroinvertebrate data collected from eight locations (four upper and four lower) along the Escalante River in June 1998 (Mueller et al. 1999). From these samples, Mueller et al. (1999) calculated the Ephemeroptera (mayfly), Plecoptera (stonefly), and Trichoptera (caddisfly) (EPT) taxa richness (insect orders sensitive to pollution), Modified Hilsenoff Biotic Index (summary of the overall pollution tolerances of taxa collected), and the community tolerance quotient (integrates biological, physical, and chemical parameters). For EPT richness, lower scores are indicative of pollution, while the Hilsenhoff Index ranges from 0 (unpolluted) to 10 (severely polluted) and the community tolerance quotient ranges from 2 (unpolluted) to 108 (severely polluted) (Miller and Judson 2011).

For the Escalante River biological (fish) community and habitat measures, we summarized data reported in Holden and Irvine (1975), Mueller et al. (1999), UDWR (2008), and Woodhouse and Fridell (2017). In general, these studies sampled fish and fish habitat in the upper reach from just above Coyote Gulch to the park boundary and in the lower reach from just above Coyote Gulch to the confluence with Lake Powell (Figure 3.7.2-1).

For the San Juan River, we summarized data published by the San Juan River Basin Recovery Implementation Program (SJRRIP), which surveys two reaches within GLCA (Schleicher 2016; Zeigler and Ruhl 2016). The upper reach is only partially within GLCA while the lower reach is located entirely within GLCA (Figure 3.7.2-1). Although focused on federally endangered species, these reports provide information on other native fishes and their habitats, as well as non-native fishes. The SJRRIP surveys sub-adult and large-bodied fishes (Ryden 2005; Schleicher and Ryden 2013; Schleicher 2016) as well as small-bodied fishes (Propst et al. 2004; Paroz et al. 2007; Paroz et al. 2008; Zeigler and Ruhl 2016; Zeigler and Wick 2019) during autumn. Surveys occurred from 1998–2010 and in 2015. In 2018, surveys for small-bodied fishes occurred in the upper reach only. Although roundtail chub, flannelmouth sucker, and bluehead sucker are all large-bodied species, the small-bodied monitoring efforts document post-larval age-0 (young-of-year) large-bodied fishes and the small-bodied speckled dace. Finally, Pennock (2019) surveyed San Juan River fish in GLCA during 2018–2019. Information on invasive aquatic invertebrates was not available.

Over the next 3 to 4 years, eligible anglers will be offered a reward of at least $25 per brown trout, which is a non-native sports fish, over 15 cm (6 in) in length removed from the Colorado River between the Glen Canyon Dam and the mouth of the Paria River. Image Credit: NPS.

3.7.4. Results & Discussion

Observed annual flow volumes for the Paria River gage were not significantly different than estimated natural flow volumes, with a mean departure of <1% (t (208) = 0.58, p = 0.56) (Figure 3.7.4-1). For the San Juan River gage, observed annual flow volumes were 14% lower than estimated natural flow volumes through 1962, after which observed flow volumes substantially departed from natural conditions (mean departure of −27%) (Figure 3.7.4-1). The Navajo Dam, which began operating on the San Juan River in 1963, is responsible for reduced flows, but there are many diversions along the river (Holden 1999). Variability in total annual as well as April–October flows for the Paria River were similar between estimated natural and observed flows (Figure 3.7.4-2). For the San Juan River gage, mean, median, and flow variability (particularly for high flows) both pre-dam and post-dam were lower than natural estimates, but there was no significant difference in the pre-dam flow vs. post-dam flow (t (90) = 1.93, p = 0.06). There was a significant difference in estimated natural flow volumes vs. pre-dam flow volumes (t (147) = 2.22, p = 0.03), which suggests that factors other than the dam are responsible for reduced flows in the San Juan River. Declines in flows were most apparent for April through June, whereas August through October base flows were similar to estimated natural flows (Figure 3.7.4-2). The San Juan River monthly hydrograph reflects a snowmelt-driven river while the Paria River hydrograph reflects a late summer rain-driven hydrograph.

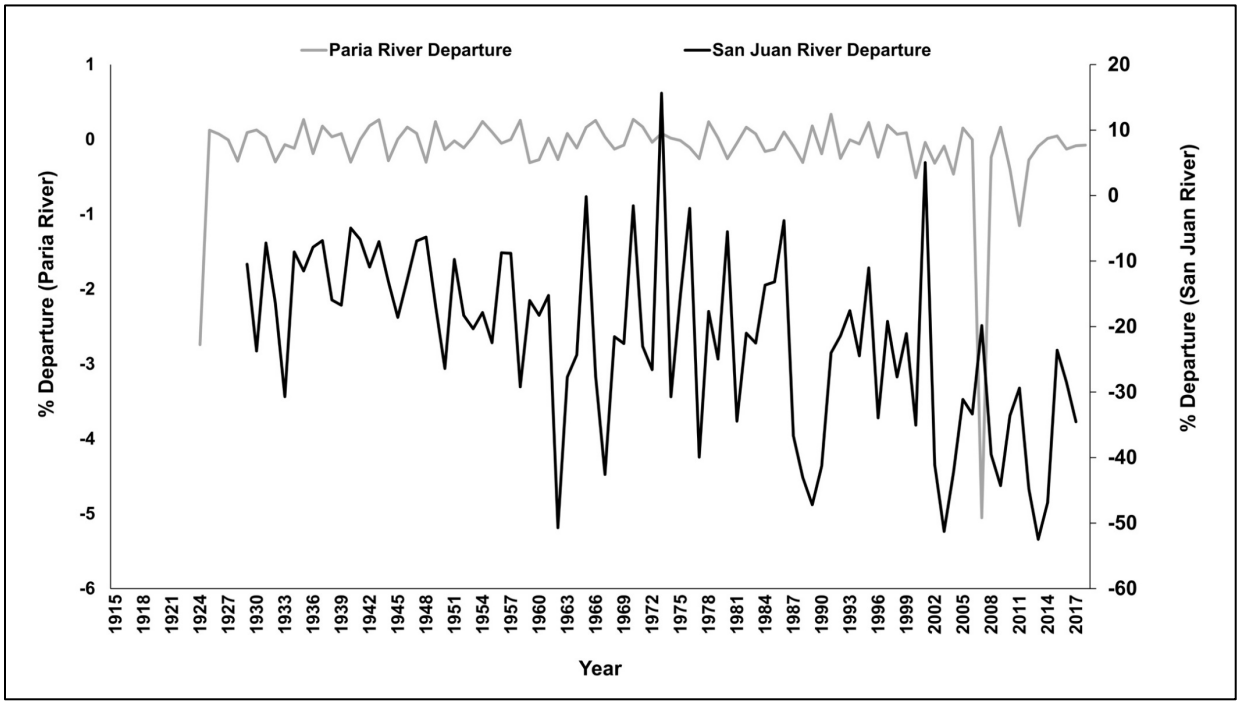


Figure 3.7.4-1. Percent departure in total annual flow from estimated natural flows for the Paria River (1924–2018) and San Juan River (1929 to 2018) USGS stream gages.

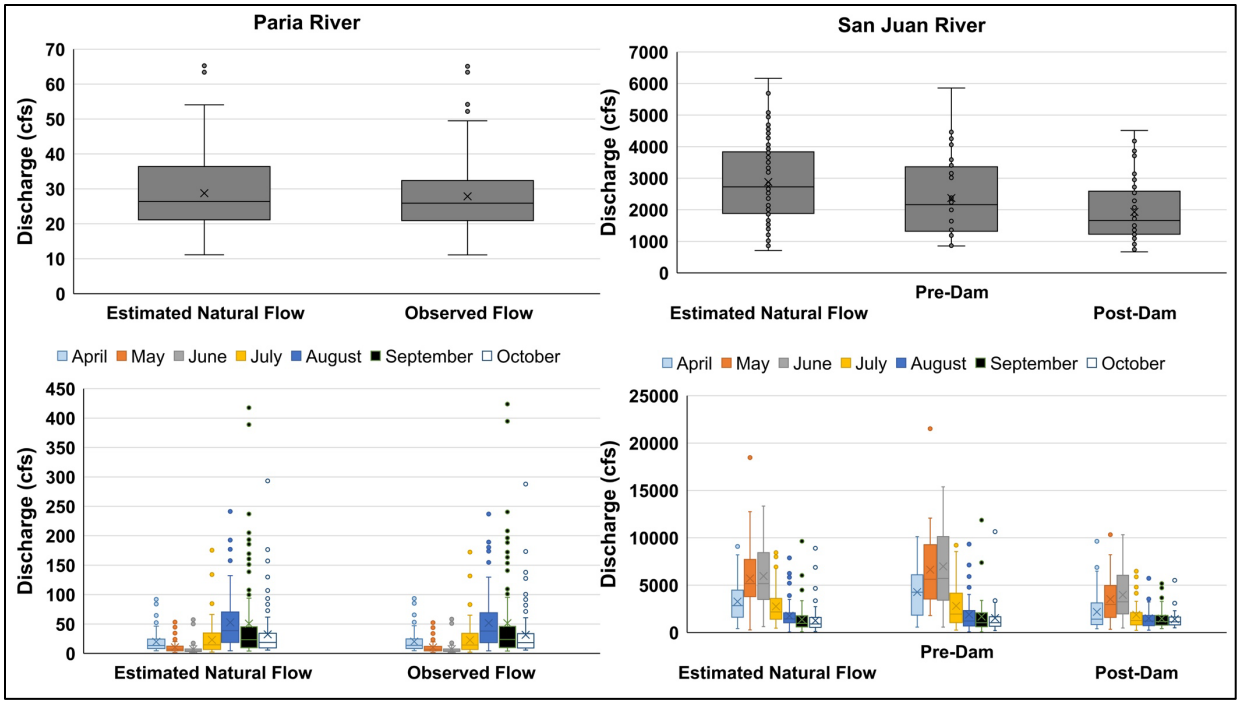


Figure 3.7.4-2. Boxplots of the mean, median, lower and upper quartiles, and outliers for estimated and observed total annual flow and monthly (April–October) flow for the Paria and San Juan rivers. For the San Juan, observed flows were separated into pre-dam (before 1963) and post-dam (after 1963) periods.

Boxplots of flow data for the Escalante and Dirty Devil stream gages show that mean annual flow, annual variability in flow, and monthly flow variability were larger during the historical period than during the contemporary period (Figure 3.7.4-3). However, only historical vs. contemporary flows were significantly different for the Escalante River (t (24) = 2.21, p = 0.02) but not for the Dirty Devil River (t (18) = 0.52, p = 0.60). The Escalante monthly hydrograph reflects a snowmelt-driven river while the Dirty Devil River hydrograph reflects a late summer rain-driven hydrograph.

Overall, these results suggest that water quantity and availability has been moderately degraded from natural or historical conditions, which indicates a fair condition. Given declines in annual discharge volumes, reduced flow variability, and changes to spring flows, additional monitoring of fish is warranted. The SJRRIP has an ongoing fish restoration program for the San Juan River, but we are not aware of similar programs for the Escalante, Dirty Devil, or Paria rivers within GLCA, though UDWR has implemented monitoring and management of fish in those rivers outside of the recreation area (UDWR 2006). Flow magnitude, duration, and amount are key factors that create and maintain suitable fish habitat (Laub et al. 2018).

For the water quality indicator, the Lower San Juan River from Lake Powell to its confluence with Chinle Creek is listed as impaired by UDEQ (2018) for aluminum, copper, dissolved oxygen, iron, mercury, maximum temperature, and *E. coli* (Table 3.7.4-1). Of this 142-km (88-mi) stretch, 113 km (70 mi) are within GLCA. This impairment listing is in part due to the Gold King Mine spill, which occurred on 5 August 2015 (USEPA 2018). Contaminated water from the abandoned Gold King

Mine in Silverton, Colorado was accidentally released by a USEPA work crew into Cement Creek, which is a tributary of the Animas River and part of the San Juan River and Colorado River watershed (USEPA 2018). The spill resulted in a spike in lead, arsenic, iron, copper, and other heavy metals in the immediate vicinity of the spill. By the time the plume reached the San Juan River, total metal concentrations had declined by three orders of magnitude (USEPA 2018). However, speckled dace, bluehead sucker, and flannelmouth sucker abundance was lower in 2015 and 2016 in the middle reach of the San Juan River, while channel catfish (*Ictalurus punctatus*) and Colorado pikeminnow abundance was higher, but these changes in abundance could not be directly attributed to the spill. Monitoring at hundreds of locations along the Animas River and San Juan River indicate that by the end of 2016; however, these heavy metals had been flushed from the system and heavy metals in fish tissues were generally low and often below detection limits (USEPA 2018). However, the Gold King Mine is just one of dozens of mines leaking contaminants in this river system (USEPA 2018).

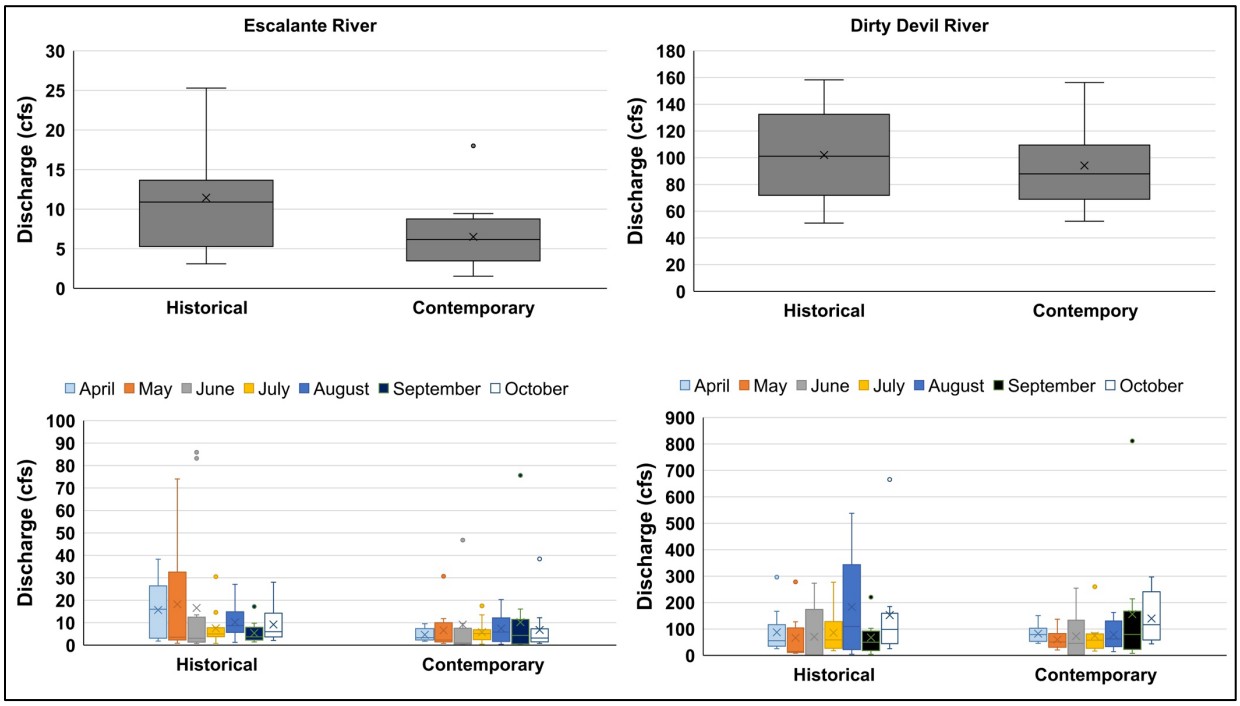


Figure 3.7.4-3. Boxplots showing the mean, median, lower quartile, upper quartile, and outliers for historical and contemporary total annual and monthly (April–October) flow data for the Escalante River and Dirty Devil River USGS stream gages.

The Paria River was also listed as impaired for *E. coli*, selenium, and suspended solids. Only 5 km (3.1 mi) of the 47-km (29.4 mi) stretch are located within GLCA. There were no impairments listed for the Escalante River or Dirty Devil River; however, Dyer et al. (2016, 2017) found several contaminants of emerging concern at the two Escalante River sampling locations (Table 3.7.4-1).

Table 3.7.4-1. List of water quality impairments for the evaluated streams.

Assessment Unit (ID#)	Description	Impairments and/or Contaminant (years listed)
San Juan River-1 (14080205-001_00)	San Juan River from Lake Powell to confluence with Chinle Creek	Aluminum (2016), copper (2014,2016), oxygen (2014), iron (2016), mercury (2016), maximum temperature (2018), *E. coli* (2018)
Paria River (14070007-123)	Utah border to Colorado River	*E. coli* (2006), selenium (2016), suspended solids (2004)
Escalante River (ESC01)	Above Coyote Gulch (upper reach)	Propachlor (2011), triclopyr (2011), besphenol A (2011), estrone (2011), pentachlorophenol (2011), tri(dichloriosoprophyl) phosphate (2011), triphenal phosphate (2011)
Escalante River (ESC02)	Below Coyote Gulch (lower reach)	Triclopyr (2012–2014), imazethapyr (2014), caffeine (2012–2014), DEET (2012–2013), phenylpropanolamine (2012–2013), triclocarban (2012–2013)

These include flame retardants (e.g., Triphenyl phosphate), insecticides (e.g., DEET), herbicides (e.g., Triclopyr), and antibacterial agents (e.g., Triclocarban). The effects of these contaminants are not well understood, nor are there criteria by which to assess levels at which these chemicals may cause harm to aquatic communities (Weissinger et al. 2018).

Mercury concentrations in dragonfly larvae in GLCA were among the highest of 100 national parks sampled from 2009–2018 (Eagles-Smith et al. 2020). In a companion study, Eagles-Smith et al. (2014) found that speckled dace sampled in 2012 at CARE, which shares a boundary with GLCA, exhibited the highest mercury concentrations of all fish sampled in 21 western national parks in the U.S. (Eagles-Smith et al. 2014). In a separate study of mercury and selenium concentration in fish across seven tributaries of the Colorado River, Day et al. (2020) found that fish in the San Juan and Dirty Devil Rivers exhibited the lowest concentration of mercury and selenium. Colorado pikeminnow and roundtail chub were two species with the highest concentration of mercury, but human-health benchmarks for most individuals were rarely exceeded (Day et al. 2020). Although both elements can be toxic above certain concentrations, selenium is an essential element required for biological functions, including reproduction (Day et al. 2020). When mercury and selenium co-occur, the latter can ameliorate some of the adverse effects of mercury (Day et al. 2020).

Mueller et al. (1999) reported 475 macroinvertebrates representing 19 taxa across the eight sites surveyed. Most (359) were collected from the lower reach, while the remaining (116) macroinvertebrates were collected from the upper reach. The dominant families were Chironomidae (non-biting midges), Hydrosychidae (caddisflies), Simuliidae (black flies), and Tricorythidae (mayflies). EPT richness ranged from 4 to 6 in the upper and lower reaches, respectively. These values are associated with slightly to moderately impacted stream quality. The Hilsenoff Biotic index ranged from 2.36–4.93, which indicates possible slight organic pollution and probable organic pollution at the lower reach. The Community Tolerance Quotient indicates issues with water quality given that the scores ranged from 87 to 100. Although these indices suggest possible issues with water quality, the data were collected in 1998. Furthermore, Weissinger et al. (2012) point out that

there is limited information about tolerance values for aquatic macroinvertebrates in the Southwest. Also, hydrologic regimes (e.g., intermittent stream, perennial desert stream, perennial mountain stream) influence benthic macroinvertebrate richness and composition apart from pollutants (Miller and Brasher 2011).

Although there are some water quality issues for the streams considered in this assessment, no significant impacts to warm water aquatic life have been reported. Therefore, the condition for this indicator is good/fair. We excluded benthic macroinvertebrates from the water quality indicator since the data were not current.

Riparian habitat along the Escalante River. Image Credit: ERWP (2017).

In the four studies we reviewed for the Escalante River fish (biological) community indicator of condition, all indicated a healthy, mostly native fish community in the upper reach and a community dominated by non-native fish in the lower reach. Holden and Irvine (1975) documented all four species in the upper reach, but bluehead suckers were absent in the lower reach. Red shiners (*Cyprinella lutrensis*) were the most abundant and observed species in both reaches. The other non-

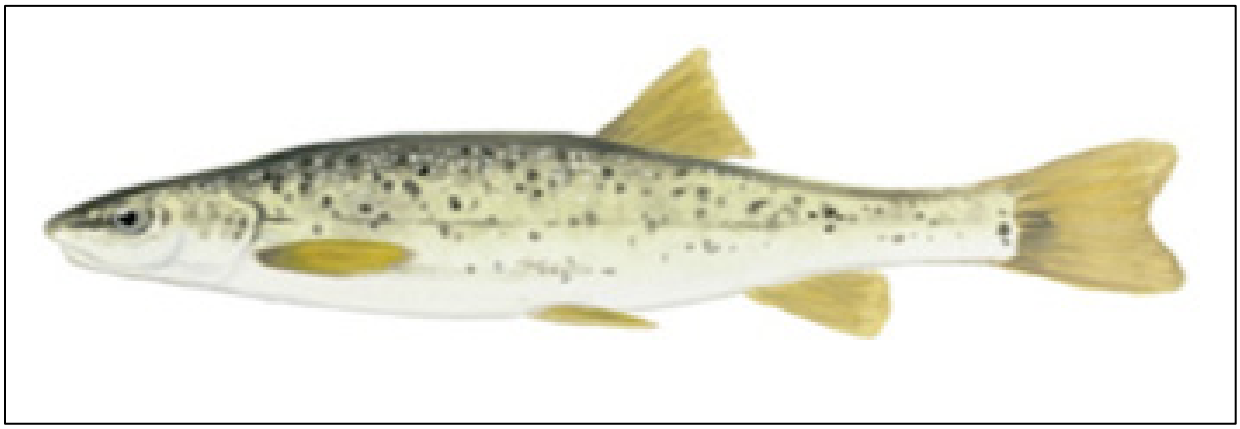
native species, which were far less common overall, were almost exclusively found in the lower reach. These included fathead minnow, common carp, channel catfish, largemouth bass (*Micropterus salmoides*), and green sunfish (Holden and Irvine 1975). McAda et al. (1977) as cited in Mueller et al. (1999) found similar results except that they also reported native cutthroat trout (*Oncorhynchus clarkii*) and non-native brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*), brook trout (*Salvelinus fontinalis*), and trout hybrids.

During the 1998 survey, Mueller et al. (1999) reported speckled dace, roundtail chub, and flannelmouth sucker in the upper survey sites, but only speckled dace and flannelmouth sucker in the lower sites. No bluehead suckers were reported at any sampling sites, but UDWR reported this species, as well as roundtail chub and flannelmouth sucker, in 2003–2004 (Mueller et al. 1999). Mueller et al. (1999) also reported non-native yellow bullhead (*Ameiurus natalis*) and striped bass (*Morone saxatilis*) in the lower reach, neither of which had been previously reported for the Escalante River. Brown trout were also encountered in the upper reach and channel catfish and carp were found in the lower reach (Mueller et al. 1999). In 2008, UDWR reported roundtail chub, flannelmouth sucker, bluehead sucker, and speckled dace in the extreme upper reach of the Escalante River in GLCA above Harris Wash (UDWR 2008). Speckled dace (56% of total catch) and flannelmouth suckers (40% of total catch) were by far the most abundant species, while bluehead suckers and roundtail chub comprised only 4% and 1% of the total catch, respectively (UDWR 2008). As in previous studies, UDWR (2008) reported that non-natives were rare in the upper reach, comprising <1% of total catch with fathead minnows and brown trout.

Woodhouse and Fridell (2017) reported similar results to those described above. In the upper reach all four native fish species were encountered, while bluehead suckers were absent in the lower reach during 2017 sampling. In the upper reach, ~99% of all individual captures were native, with speckled dace being the most common. However, a single non-native red shiner was captured in the upper reach. In the lower reach, the three native species represented only ~9% of the total catch. The remaining ~91% was comprised of five non-native species, including gizzard shad (*Dorosoma cepedianum*), channel catfish, common carp, and black crappie (*Pomoxis nigromaculatus*). Of these, the red shiner followed by the gizzard shad were the most abundant. The other non-native species were uncommon or rare. These results indicate consistent presence of all four native species in the upper reach of the Escalante River in GLCA. The lower reach, however, is dominated by a variety of non-native species (13 non-natives were reported in the four studies), and the bluehead sucker is absent. The non-native red shiner is most prevalent, while other non-native species are less abundant. Non-native species enter the Escalante River from Lake Powell, and this is considered the most significant threat to the native fish community in the lower reach (UDWR 2006).

For the biological community in the lower reach of the San Juan River, bluehead suckers are all but absent, although a small number of adults were captured in four of the five years between 2003 and 2007 but not during 2008–2010 or 2015 surveys (Schleicher and Ryden 2013; Schleicher 2016). However, Pennock (2019) reported capturing two adult bluehead suckers in the lower reach during spring surveys in 2018–2019. Prior to 2003 (1994–2002), bluehead suckers were never captured in the lower reach (Schleicher and Ryden 2013). In the upper reach, adult bluehead suckers have been

captured annually from 1994 to 2010 and in 2015 (i.e., all years of monitoring), although in small numbers (Ryden 2005; Schleicher and Ryden 2013; Schleicher 2016). No young-of-the-year bluehead suckers were captured during small-bodied fish surveys in either the upper or lower reach, but Pennock (2019) reported early life-stage bluehead suckers in 2018–2019 in the lower reach. Although bluehead suckers are rare in GLCA, they are common farther upstream where suitable cobble-dominated habitat is more abundant (Ryden 2005; Schleicher and Ryden 2013; Schleicher 2016).



The speckled dace is a minnow that is common throughout the western U.S., including the Colorado River Watershed. Illustration Credit: UDWR/Ben Sutter.

In the upper reach of the San Juan River, three of the four species have been documented in most years that surveys occurred (Schleicher and Ryden 2013; Schleicher 2016; Zeigler and Wick 2019). Adult and young-of-the-year flannelmouth sucker and speckled dace are captured in all survey years but are uncommon in both the lower and upper reaches; however, SJRRIP surveys indicate successful recruitment of these two species in both reaches (Schleicher 2016; Zeigler and Ruhl 2016). No roundtail chub have been captured in the San Juan portion of GLCA, and this species is extremely rare riverwide (Schleicher and Ryden 2013; Schleicher 2016; Zeigler and Wick 2019).

Non-native species dominated San Juan's lower and upper reaches with at least 14 species documented. Common carp, channel catfish and gizzard shad are the most common non-native fish. Channel catfish abundance has remained stable in the lower San Juan despite 14 years of removals (Hines 2018). Red shiners are also abundant in both reaches. Other non-natives in the San Juan River include fathead minnow, largemouth bass, western mosquitofish (*Gambusia affinis*), green sunfish, smallmouth bass (*Micropterus dolomieu*), striped bass, black crappie, walleye (*Sander vitreus*), threadfin shad (*Dorosoma petenense*), and plains killifish (*Fundulus zebrinus*) (Zeigler and Wick 2019). Non-native fish dominate both reaches in terms of abundance and richness. Dams, lack of habitat, and hybridization are the primary threats to fish in the San Juan River (UDWR 2006).

Lake Powell's lake elevation was 29 m (95.09 ft) below full pool level when this photo was taken in March 2021. Image Credit: NPS.

Length-frequency histograms of the roundtail chub, bluehead sucker, and flannelmouth sucker indicate multiple age classes and successful recruitment during 2017 in the upper reach of the Escalante River (Woodhouse and Fridell 2017). This was also true for flannelmouth sucker in the lower reach, but not for roundtail chub (bluehead sucker absent). In the San Juan River, Schleicher (2016) reports that flannelmouth sucker annual captures in high numbers indicate successful reproduction and recruitment. Although capture rates have varied year-to-year, the population is stable (Schleicher 2016). The SJRRIP surveys show that populations of speckled dace and flannelmouth sucker are found in stable numbers within the riverine portions of GLCA.

Because some native species are absent or severely reduced in numbers and the community is dominated by non-native species, the condition for the biological community is poor for the San Juan River and the lower Escalante River. The upper Escalante River in GLCA appears to be in good condition. We did not consider invasive invertebrates in determining condition for this measure due to the absence of data.

Kayaking is a popular activity at GLCA and canyon areas can become congested with several boaters. Image Credit: NPS.

In the Paria River, the current status of flannelmouth sucker is unknown (UDWR 2006), but in 1996 McIvor and Thieme (1999) reported successful spawning of this species in the Glen Canyon reach. McIvor and Thieme (1999) also reported presence of this species during 1991–1992 and 1994–1995. However, Weiss et al. (1998) noted that an increase in mean lengths of spawning flannelmouth suckers between 1981 and 1993 suggests an aging population with relatively low recruitment to sexual maturity. Threats from de-watering have been cited as the primary threat to native fish in the Paria River (UDWR 2006). In the Dirty Devil River, all four native species are present, but their current status in GLCA is unknown (UDWR 2006; Laub et al. 2018). Roundtail chub were also historically present in the upper Dirty Devil (UDWR 2006). Although the UDWR has surveyed the Dirty Devil and Paria rivers, there are no monitoring locations in GLCA.

The AZGFD periodically collects fish from the lower Paria River for laboratory studies. From 2016–2018 AZGFD seined the lower Paria during spawning (April) to collect eggs and milt for a laboratory/hatchery study investigating hybridization between flannelmouth suckers and razorback suckers (AZGFD, J. Boyer, fisheries biologist, e-mail communication, 6 January 2021). Due to ongoing droughts and the flashiness of the Paria River, there are few years in which flannelmouth suckers successfully spawn, with few if any eggs or young surviving; the temperature of the Colorado River below the dam is too cold for successful sucker spawning (AZGFD, received by K. Hyde, NPS Chief of Science and Resource Management, 5 January 2021). Adult flannelmouth suckers continue to be captured in electrofishing monitoring trips conducted by AZGFD in the mainstem Colorado River below the dam, including in the large backwater located at Rivermile–12. Two flannelmouth suckers were captured in this backwater in March 2021 during brown trout removal efforts (NPS, K. Hyde, NPS Chief of Science and Resource Management, 19 April 2021).

The Colorado River narrows into steep-walled canyons after it leaves Lake Powell, flowing south from GLCA into Grand Canyon NP. Image Credit: NPS.

Holden and Irvine (1975) noted that the lower reach of the Escalante was entrenched with a "monotonous string of sand runs and deep pools." Habitat diversity there was low compared to the upper reach. At the eleven stations surveyed for fish along the Upper Escalante, runs (65.9%) made up the majority of habitats sampled, followed by pools (20.5%), riffles (12.7%), and backwater (0.9%). Sand was the most common substrate encountered (60.0%), followed by gravel (21.8 %),

cobble (15.5%), bedrock (1.4%), silt (0.9 %), and boulder (0.5%). Along the Lower Escalante, the majority of habitats sampled were runs (55.0%), followed by pools (36.0%), riffles (8.0%), and backwater (1.0%). Sand was the most common substrate encountered (72.0%), followed by gravel (15.0%), cobble (11.0%), and silt (2.0%). Woodhouse and Fridell (2017) characterized the lower reach as "shallow, sandy runs interspersed with pools surrounding large boulders." These conditions enable non-native species to thrive at the expense of native species and are likely the direct result of Glen Canyon Dam. Prior to the dam, much of the sediment was carried downstream during spring runoff and flooding, but the annual fluctuations in Lake Powell inundate the lower portion of the Escalante River when lake water levels are high (Woodhouse and Fridell 2017). The absence of bluehead suckers from the lower reaches of the Escalante and San Juan rivers is due to the lack of cobble-dominated habitat, but non-native species also likely play a role (Schleicher and Ryden 2013). A natural flow regime favors recruitment of native fish through the increased quantity and quality of spawning habitat and food resources (Gido and Propst 2012).

The Bureau of Reclamation manages Glen Canyon Dam's water flow, which may expose patches of green algae (lower left side of water) that were previously underwater when water levels were higher. Image Credit: NPS.

The amount of low-velocity habitat is important for early life stages of fish (Lamarra and Lamarra 2018). The lower San Juan River reach has "large amounts of ephemeral sand bars and associated backwaters" (Lamarra and Lamarra 2018). Both the upper and lower reach gained low-velocity

habitat from 2016 to 2017. The upper reach has roughly 40% less low-velocity habitat than the lower reach. From 2016 to 2017, there were extensive changes to stream habitat as a result of high spring floods. Sustained flows between 5,000 cfs and 8,000 cfs mobilize cobble substrates and flush fine sediment downstream. Overall, several years of sustained floods (i.e., >50 days over 5,000 cfs) has "contributed to the cleaning and redistribution of silt" (Lamarra and Lamarra 2018). Beginning in 1999, the recommendation of sustained spring flows has been implemented at the Navajo Dam, which has improved in-stream habitat (Holden 1999; Lamarra and Lamarra 2018). These results indicate an improved condition for the San Juan River; however, sediment deposition at the confluence of the San Juan to Lake Powell have created a geomorphic barrier on the San Juan River (Cathcart et al. 2018).

Eventually, this change in hydrology and sedimentation led to the emergence of a waterfall barrier on the San Juan River in 1989 (Cathcart et al. 2018). The waterfall effectively isolated threatened and endangered species and species of concern from moving upstream. Subsequent shifts in hydrology inundated this waterfall by 1995, which allowed fish passage, but a new waterfall formed in 2001 after water recessions in the 1990s (Cathcart et al. 2018). The waterfall is a complete barrier to fish travel except during exceptionally high flows (e.g., 2011) (Cathcart et al. 2018). Although waterfalls have not formed on the Escalante or Dirty Devil rivers as a result of the Glen Canyon Dam, altered river delta sedimentation has effectively cut off the movement of native fish from the lake to upstream habitat in these rivers (Woodhouse and Fridell 2017). Continued declines in the storage of water in Lake Powell will exacerbate these issues at the river deltas above the dam. As of December 2020, Lake Powell was at 42% of full capacity (Bureau of Reclamation 2021). In contrast, alluvial deposits at the mouth of the Paria River form naturally (McIvor and Thieme 1999).

These four species all require different amounts of pools, runs, riffles, low-velocity habitat, and a mix of various substrate features (Bower and Hubert 2008). Roundtail chub prefer larger rivers with slow-moving, deep pools and riffles for cover and feeding, but they also reside in small tributary streams. Flannelmouth suckers are wide-ranging species that utilize a variety of habitats including warmwater habitats up to 27 °C (80.6 °F), while bluehead suckers prefer rocky substrates that tend to occur further upstream than habitats typically occupied by flannelmouth suckers or roundtail chubs (Bezzerides and Bestgen 2002). Speckled dace are found in a variety of habitats, though they are most common in "riffles and runs with moderate to rapid velocity water over gravel and cobble substrates" (Holden 1999). Because of these differences and limited available data, we did not assign a condition to the habitat indicator.

Park managers question how the native fish community along the Escalante River may be affected by Russian olive removal, especially in the interim until native and/or other non-native shrub and tree species fill in the riparian plant communities. There are very few studies on the effects of Russian olive on native fishes and even fewer on the effects of Russian olive removal on the aquatic community (Shafroth et al. 2010). Russian olive control could influence the aquatic invertebrate community that serve as prey for many species of fish. Additionally, the removal of Russian olive may also change the amount and timing of leaf or woody input into stream channels. Allochotonous (sediment or rock that originated elsewhere) organic matter increased 25-fold along an Idaho stream

after invasion by Russian olive (Mineau et al. 2011). Shafroth et al. (2010) also suggest that removing Russian olive can be an effective tool for managing native fish habitat, but the cascading effects of Russian olive removal remain an area of needed research. One effect may be a decline in soil and water nitrogen. Russian olive increases the bio-availability of nitrogen into streams (Mineau et al. 2011) and soils (DeCant 2008), but increased nitrogen could lead to eutrophication and reduced oxygen.

As with amphibians and other aquatic life, threats from airborne or atmospheric contaminants, such as heavy metals, mercury, and nitrogen fertilizers warrant continued and perhaps more intensive monitoring of water quality for fishes. More than 85,000 chemicals are of current commercial use in the U.S., half of which lack adequate toxicological studies for humans and the environment (Robichaud 2020). Semi-volatile organic compounds, including some persistent organic pollutants, and metals can and do travel substantial distances through the air, eventually settling into water and soils in more remote locations, including national parks (Landers et al. 2010). Weissinger et al. (2018) found that during 2012 to 2016 at least one contaminant of emerging concern was found in water or sediments in eight national parks, including GLCA. Atmospheric deposition of pollutants can then accumulate in fish and their prey, which could contribute to population declines (Eagles-Smith et al. 2014).

This assessment/gap analysis included four tributary rivers in GLCA, with a summary of conditions for indicators shown in Table 3.7-4-2. While there are ongoing studies for the Escalante and San Juan rivers, including robust management of the latter stream, there are few data for the Dirty Devil and Paria rivers.

Table 3.7.4-2. Fishes condition ratings* summary.

Indicator	Condition Rating	Trend	Condition Evaluation
Water Quantity and Availability (San Juan, Escalante, Dirty Devil, Paria rivers)	Fair	Deteriorating	Two of the four streams exhibited moderate departures from natural or historical conditions in total annual flow, seasonal flow, and variability in flow. The Paria and Dirty Devil rivers, however, did not appear to depart from natural conditions. Confidence is high due to current and long-term data.
Water Quality (San Juan, Escalante, Dirty Devil, Paria rivers)	Good/Fair	Unknown	No significant impacts to warm water aquatic life were reported. Mercury and emerging contaminants are not well studied. Data for benthic macroinvertebrates were limited. Confidence is medium because of the variability in data availability.
Biological Community (Lower Escalante and San Juan rivers)	Poor	Stable	Some native species are absent or severely reduced in numbers and the community is dominated by non-native species, thus the condition for the biological community is poor for the San Juan and the lower Escalante rivers. Confidence is high due to current and long-term data.

* See Appendix B, Table B-4, for the 5-level condition rating statements for each indicator.

Table 3.7.4-2 (continued). Fishes condition ratings* summary.

Indicator	Condition Rating	Trend	Condition Evaluation
Biological Community (Upper Escalante River)	Good	Stable	All four species are consistently present and length-frequency data indicate stable populations. Confidence is high due to current and long-term data.
Habitat Quality and Availability (Escalante and San Juan rivers)	Unknown	Unknown	Data are limited and needs vary by species so condition is unknown based on currently available data.

* See Appendix B, Table B-4, for the 5-level condition rating statements for each indicator.

Chapter 4. Management Considerations

Chapter 2 of the NRCA report considered the direct or indirect impacts that selected drivers and/or stressors may have (now or in the future) on focal resource conditions at GLCA. Drivers and stressors often exert influences on resource conditions over a broader regional or landscape scale and may arise from inside or outside of GLCA, which influences the feasibility of taking action and affecting change in natural resource conditions.

A view of the Escalante River pre- (left) and post-Russian olive control (right). This is one of the many management responses GLCA managers employ in cooperation with the Escalante River Watershed Partnership to improve resource conditions. Image Credits: NPS.

Chapter 3 provided condition evaluations for each park-selected focal natural resource. The project team developed condition assessments for resources when adequate data were available or when expertise could be engaged to assess one or more indicators of condition. Resources lacking adequate data or expertise were evaluated at a lower level of evaluation (gap analysis) so that park managers could still receive useful condition-related information for future consideration.

This chapter suggests useful activities or responses based on a manager-scientist review of key condition findings and a discussion of "next steps". Responses that include multiple natural

resources, other park divisions, and/or partnerships will provide managers with a comprehensive portfolio of actions to consider in the near-term or over a longer-term planning horizon.

4.1. Manager-Scientist Review

To finalize GLCA's NRCA process, a manager-scientist meeting was held to review the condition findings and implications for each evaluated resource. Another meeting outcome was to identify near-term and future responses/strategic actions that may help managers further understand, maintain and/or improve resource conditions. These responses and actions consider the drivers and stressors occurring within and surrounding the park. Some of these influences can be directly managed through specific actions (e.g., non-native invasive plant control), while others are beyond a manager's ability to change (e.g., drought, climate change). Some require an inter-divisional focus and effort, while others benefit from external agency partnerships (e.g., watershed groups) due to the scale of the resource and its drivers or stressors. Thus, a more comprehensive, multi-resource/disciplinary and inter-divisional strategic approach when targeting follow-on activities or actions can greatly benefit resource resiliency and management response toward achieving resource management goals.

To facilitate the process of identifying manager responses during the manager-scientist meeting, a conceptual model of the priority drivers and stressors was presented for each resource, depicting the interactions between these drivers, stressors, and focal resource. Appendix C, Figure C-1, includes a combined conceptual model for all resources, drivers, and stressors reviewed during GLCA's manager-scientist meeting, which was held on January 14 and 15, 2021. In addition, a simpler, tabular depiction of the model is presented in Table C-1. This type of information may be useful for developing future impact analyses during various park planning efforts and is scalable to accommodate changing drivers, stressors, and management priorities over time.

Following the review of each resource's conceptual model, a matrix that included seven action categories (Table 4.1-1) and each resource's primary drivers and stressors, was used to guide the manager response discussion. The action categories were selected from the Conservation Measures Partnership (2016) *Classification of Conservation Actions and Threats*, which defines a common nomenclature to support collaboration among conservationists and consistency across NRCA reports, and from the NPS Resource Stewardship Strategy activity categories (NPS n.d.). These combined categories are intended to capture all levels of park management actions, thus are broadly defined and can be tailored to meet each park's needs, now or well into the future.

Table 4.1-1. Action categories used to facilitate manager-scientist discussion of responses.

Action Categories [1]	Description [2]
Land, Water, or Species Field-based Management	These "on-the-ground" actions directly manage or restore sites, individual or groups of species, and/or ecosystems by targeting or mitigating a stress or threat(s).
Research, Monitoring, & Inventory	These actions collect data that can ultimately be applied to inform other conservation actions.
Education & Interpretation	These are actions directed at reducing threats by increasing positive behaviors. These include raising awareness of key issues at targeted audiences to affect behaviors.
Partnerships	These actions create and provide knowledge and data-sharing and capacity to address conservation goals on a larger scale.
Zoning & Planning	These types of actions create the conditions necessary for other conservation efforts to ultimately succeed.
Law Enforcement	These actions monitor and enforce compliance with existing laws, policies, and guidance to deter threats or promote positive actions.
Laws, Policies, & Guidelines	These actions develop and influence legislation, policies, and voluntary standards affecting conservation.

[1] Categories were adapted from the Conservation Measures Partnership (2016) actions classification levels v2.0 and common NPS Resource Stewardship Strategy activity categories v3.0 (NPS n.d.).

[2] Descriptions extracted and/or adapted from Conservation Measures Partnership (2016) actions classifications.

4.2. Review Outcomes Summary

Potential management responses, as identified during the GLCA manager-scientist meeting, are summarized by focal resource and action category in Figure 4.2-1 and by focal resource and its priority drivers and stressors in Figure 4.2-2 (note that amphibians and northern leopard frog responses were combined in both figures since most of the identified actions were understandably the same).

Approximately 130 manager responses across the seven focal resources were represented in all seven action categories except for tinajas and amphibians in the law enforcement category and tinajas in the laws, policies, and guidelines category (Figure 4.2-1) (as it wasn't viewed as an action that could help at this time, at least given the park's present management approach). The greatest management need identified (37% of the responses) was acquiring additional information through research, monitoring, or inventories to better inform management actions. The next greatest management needs were field-based management activities (19%) (e.g., erecting fencing, controlling non-native invasives) and developing partnerships (17%), especially to address the larger-scale, watershed-based resource conditions and stressors.

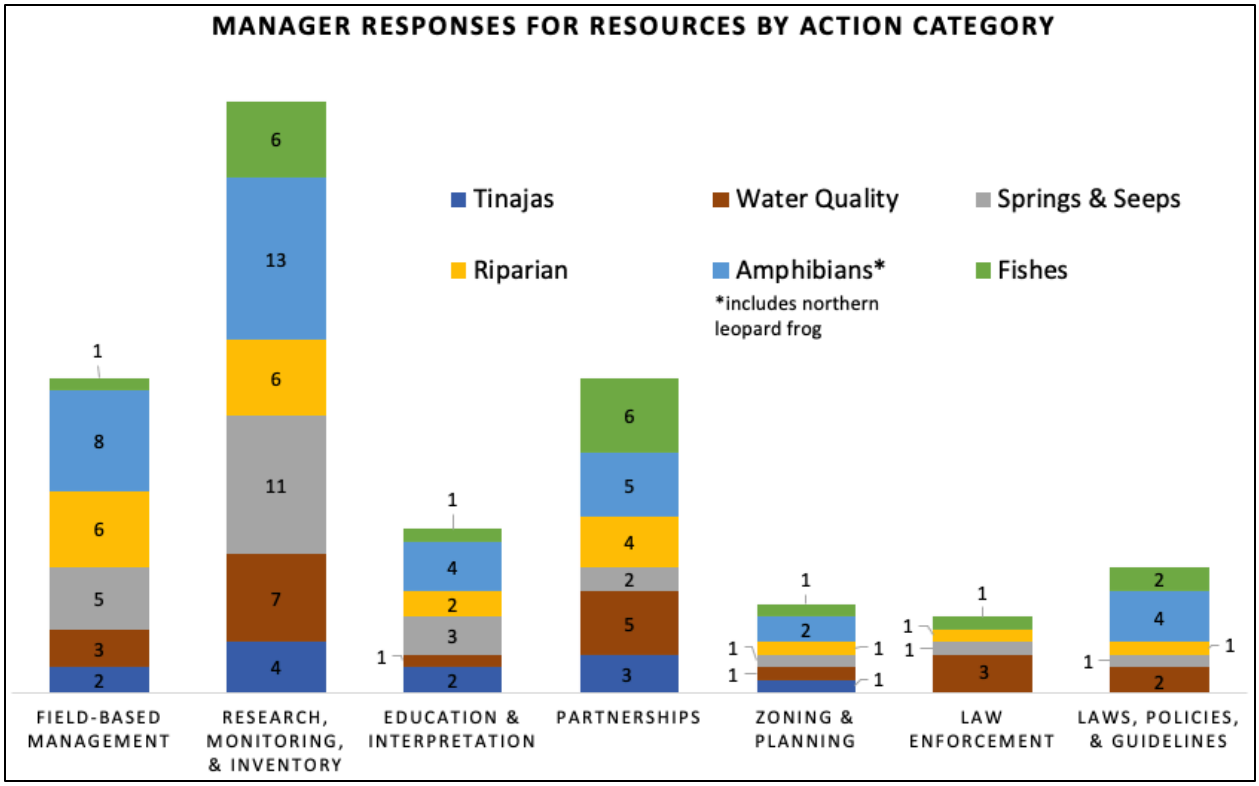


Figure 4.2-1. The proportion of manager responses by focal resource and action category that were discussed during GLCA's manager-scientist meeting.

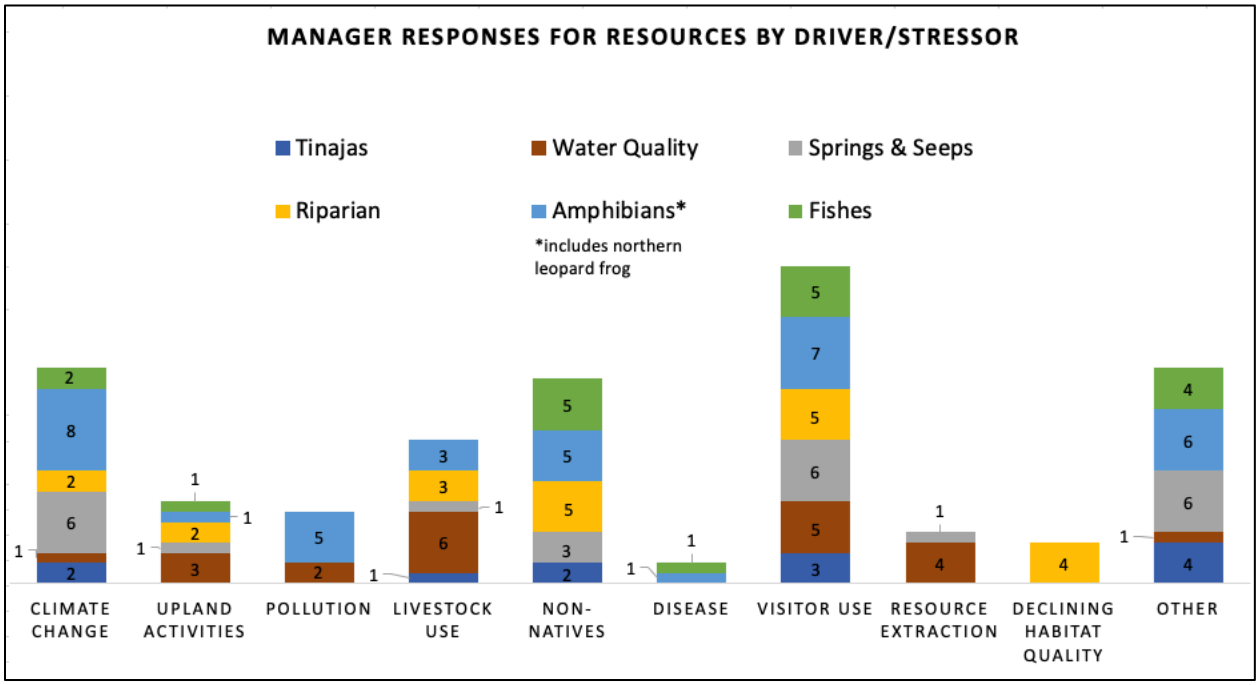


Figure 4.2-2. The proportion of manager responses by focal resource and driver or stressor that were discussed during GLCA's manager-scientist meeting.

Many responses, including education & interpretation and law enforcement, were identified as potential strategies for collaborating with other park divisions to engage with visitors and partners to manage resources more effectively through increased awareness and enforcement of area closures or unpermitted activities (e.g., campfires). Resource responses that included zoning, planning, laws, policies, and guidelines were identified, with the understanding that these may warrant a shift in management priorities, if for example, a species becomes listed as threatened or endangered in the future, or if managers need to identify protective measures for species and their habitats for various park zoning and planning initiatives (e.g., backcountry or ORV plans).

Manager responses for focal resources by their drivers and stressors (shown in Figure 4.2-2) reveal that responses related to climate change and visitor use were identified across all evaluated resources, although more actions were identified for visitor use (23% [31/133] vs. 16% [21/133] of total responses). The higher number of responses for visitor use underscores GLCA managers' engagement approach to interacting and informing visitors about the park's natural resources. In some cases, individual responses were described as providing benefits to multiple focal resources (refer to driver/stressor categories of livestock use, non-natives, upland watershed activities, and a category of "other" in Figure 4.2-2). Examples of responses that conferred cross-cutting benefits include identifying areas of connectivity for future restoration of amphibian habitat and monitoring for the occurrence of rockfalls at spring and seep locations. Disease and declining habitat quality were more resource-specific stressors and may have been used as an indicator of condition or measure in the Chapter 3 evaluations if data were available (i.e., presence/absence of disease in northern leopard frogs).

Not only were the identified actions helpful in formulating potential future management activities, GLCA managers also identified the scalability of the response matrices as an important characteristic that would help them respond to changing drivers, stressors, and park priorities over time.

4.3. Review Outcomes by Focal Resource

Activities and actions (i.e., responses) discussed during GLCA's manager-scientist meeting are presented in Appendix D (Tables D-1 to D-7) and summarized for each focal resource in the following sections. Any manager question/need listed in Appendix A that remained unanswered throughout the report is included in the focal resource response summaries below to provide useful information for improving understanding, thus clarifying management action(s) for the resource in the future. *Suggestions regarding future studies or other actions to address the unanswered manager questions/needs are italicized.*

4.3.1. Tinajas Summary

Tinajas are driven by surface water, which in turn is driven by changing precipitation patterns (both amount and timing). While managers cannot influence climate, they can prioritize the management of known tinaja locations based on the presence of vegetation, which usually indicates more available water. A mapping exercise showing potential tinaja locations was completed in this NRCA study for a small area of the park. *Evaluating the park's remaining area for additional tinaja locations may be a beneficial focused study and further answer the managers' question of "where are tinajas located in GLCA?"*

Equipped with a more comprehensive understanding of tinaja locations throughout the entire park, a strategy for prioritizing these locations could be developed. Given the widespread extent and rugged terrain of GLCA, which makes access difficult, one consideration would be to manage tinajas in conjunction with high priority spring locations to maximize field time. Another consideration would be to evaluate tinaja and spring locations and create a distribution map that prioritizes dispersion across the landscape, providing water accessibility over greater areas. *Identified priority tinajas could then be managed for non-native invasive plants, livestock access, and visitor use, and studies could include wildlife use monitoring, including amphibians and mammals, presence of water, and water quality, including the effects from sunscreen or E. coli contamination, and documenting the presence of endemic vegetation, if any.* Knowing the priority locations would also inform GLCA's backcountry management planning efforts and focus potential groundwater studies. The studies would address a significant data gap and provide managers with information about recharge zones and potential connections between tinajas and springs and seeps.

Woodhouse's toad uses temporary pools of water, such as those found in tinajas, for breeding. Image Credit: NPS.

With changing precipitation patterns, including droughts, tinajas may serve an increasingly important role for toads and canyon tree frogs to complete their life cycles. Release of tamarisk leaf beetles (*Diorhabda carinulata*) may also maintain water availability in tinajas in areas the beetle is unable to reach on its own due to location isolation. The Waterpocket Fold has a high likelihood of tinaja occurrence due to its geologic strata and is the feature that joins GLCA and CARE. Partnering with

CARE (and other Colorado Plateau national parks and BLM) to monitor and manage tinajas on a landscape-level may represent the first of its kind program and offer a great opportunity to enlist help from visitors to maintain the water quality of these important surface water features. Information that is discovered through monitoring the wildlife and plants of tinajas can be used to develop educational or interpretive programs.

4.3.2. Springs & Seeps, including Water Quality, Summary

The role of water quality to water health is similar to that of a canary to the air quality in a coal mine—they reveal important conditions of the environment; and while water quality data have been intermittently collected for springs & seeps at GLCA, the data gaps summarized in the gap analysis evaluation reflect the need for a standardized research and monitoring program. Recently, GLCA managers developed a more comprehensive, long-term springs monitoring protocol for collecting data at approximately 20 hanging gardens. This effort began in 2019 and will likely include surveys of five spring every year to help inform future management actions; however, monitoring water quality is only one aspect of informing timely management response for springs & seeps. *Continued monitoring of erosion, including rockfalls, downcutting of channels, and livestock use should also be included in a long-term data collection program, especially to determine if adjustments to livestock grazing periods or AUMs should be made. GLCA's AUM locations were not available to further assess the potential resource impacts in these areas.*

Because springs & seeps are primarily-groundwater environments (although upslope tinajas and precipitation events may also play a role in spring recharge (GLCA, K. Hyde, NPS Chief of Science and Resource Management, review, 19 April 2021)), *the biggest threat to shaded gardens and springs in alcoves is a decline in groundwater discharge due to changing precipitation—amount, duration, and timing—underscoring the pressing need for groundwater studies throughout the park (also a need cited in the tinajas summary in section 4.3.1).* Potential evapotranspiration for exposed hillslope springs is likely a serious concern (GLCA, J. Spence, Deputy Chief of Natural Resources & Chief Scientist, pers. comm, 11 May 2021). In addition, documenting the array of native species, including endemics, is critical prior to potential extirpation, especially as the climate continues to rapidly change.

Prioritizing spring & seep locations for management action is important given the vast amount of area where springs occur. Activities may include capturing water in pools to mitigate the effects of climate change, assisting migration for certain endemics, and controlling species such as non-native Russian olive and tamarisk, which absorb large amounts of water. Backcountry users can be informed of the importance of these resources and be enlisted to help maintain water quality by limiting their contact with the water and refraining from starting fires. More frequent livestock water tank maintenance will likely increase the amount of water accessed by livestock and native ungulates, which may reduce the use of natural springs.

Springs are especially common throughout the Escalante Watershed, and GLCA managers are actively involved with the Escalante River Watershed Partnership in protecting resources within that area. Additional partnerships for protecting and managing springs in other watersheds throughout the

park and surrounding region were also identified as a potential management action in addition to working with both NPS and BLM law enforcement.

4.3.3. Riparian Zone Summary

While the control of tamarisk in riparian areas has been successful, it has resulted in areas of die-off, specifically in areas where the tamarisk leaf beetle has expanded from initial releases by the U.S. Department of Agriculture outside of GLCA. The dead tamarisk throughout these control areas may serve as a source of firewood, providing fuel for visitor fires. This has the potential of impacting areas of high management priority, such as riparian habitat, if escaped campfires were to ignite the dead/down tamarisk in those environments. This is something that may warrant restrictions on the number of visitors to certain areas and that law enforcement could enforce.

Even though tamarisk control has been effective, one of the most significant stressors affecting the riparian zone remains the invasion of non-native plants. While robust and intensive treatments to control Russian olive and a few other invasive species have occurred along the Escalante River, other riparian zones, such as along the Dirty Devil River, are heavily invaded by non-native plants. Many species, like ravenna grass, require multi-year treatments to be effective. *Expanding colonies of tamarisk beetles may continue to reduce the footprint of tamarisk within the riparian zones and time will tell if they are replaced by native or non-native plant species; a research study would provide valuable manager response information. Furthermore, warmer and drier conditions stress native riparian plant communities while giving a competitive advantage to invasive plants, thus both control work and research activities are identified as management responses to understand how plants will respond to changing conditions and which plants will colonize the riparian habitat.*

Beavers (*Castor canadensis*) are keystone species for functioning riparian areas and need to be further monitored to provide information for management purposes; however, they have decimated the limited cottonwoods and willows in areas, especially at restoration sites, where trees were not protected adequately to deter their activity. Beaver dam analogues were identified as a potential management strategy for restoring some degraded riparian areas where adequate food and building materials are available and stream geomorphology allows functioning dams to be built. This may also improve conditions of habitat with high cattle-grazing impacts. While erecting exclosures and fencing to manage grazers is difficult, it's possible. Therefore, similar to the suggestion for tinajas and springs & seeps, prioritizing riparian areas to target a management response of fence construction would be beneficial.

To help managers maintain and/or improve riparian conditions, both in the park and in the surrounding region, several partnerships were identified: Grand Staircase-Escalante NM, Escalante River watershed partners, Sierra Club/wilderness volunteers, and BLM lands along the San Juan, Dirty Devil, and Paria rivers, and Navajo Nation lands along the San Juan River. Other possible partners include farming organizations, private and state landowners, and managers dealing with degraded lands that are being used for cattle production.

4.3.4. Amphibians, including Northern Leopard Frog, Summary

Reintroductions of amphibians in small wetlands near Horseshoe Bend and ongoing monitoring have been conducted by the USFWS. Identifying other areas of high connectivity for future restoration, while limiting or guiding visitor use within those areas, were identified as future manager responses, especially given the loss of northern leopard frog sites over the years. *Additional and properly timed amphibian and northern leopard frog surveys in historically occupied habitat areas is a priority in addition to water quality monitoring to identify contaminants of emerging concern.*

Effects of increased visitor use, with riparian areas and springs serving as preferred camping sites, bring a host of water quality and over use of amphibian habitat, along with concerns over handling of captured amphibians. GLCA managers are developing an ORV plan that needs to consider high priority species, such as the northern leopard frog. The dust generated from ORVs on habitat is also not well understood in the park, and high priority areas are currently not well known. Also, similar to tinajas and riparian habitat, erecting exclosures to limit livestock access and removing non-native invasive plant and animal (e.g., bullfrogs, crayfish) species will improve habitat conditions for amphibians.

There is great potential for partnerships with the Utah and Arizona fish and game and environmental quality (water) departments; BLM on prioritizing grazing allotments; the adjoining large landowners, including other NPS park units, Navajo Nation, and BLM to conduct monitoring and management actions on a larger scale; and with the Grand Canyon Wildlands Council and other conservation partners for protecting and restoring amphibians and their habitat along the Colorado River and throughout GLCA. In addition, tinajas could be monitored for toad and tree frog use, especially to serve as longer-term breeding habitats.

4.3.5. Fishes Summary

Declining habitat quality related to the extent of habitat areas, especially shorter stretches of perennial streams with ample water flow and increasing temperature, is of research interest. *Additional monitoring responses include identifying which species are replacing tamarisk and Russian olive as riparian shade species*, which diseases and parasites are most impactful to the native, non-game fish species of interest, and what impacts may result if the invasive grass carp (*Ctenopharyngodon idella*) or additional predatory non-game species move into previously unoccupied habitat. Additional management responses may include restricting ORV use in areas of habitat priority and evaluating the use of increasing backcountry use in specific areas to protect both habitat and fish species. *Contaminants of emerging concern are not well studied nor are benthic macroinvertebrates and represent data gaps. Partnering with the Arizona and Utah fish and game agency biologists may help inform these gaps.*

Other responses for managing the conditions of fish include enforcing restrictions on the use of live bait and incentivizing the capture and keep of invasive predatory species, such as catfish that have the potential to further impact native populations. *Again, partnering with Utah and Arizona fish and game agencies, along with active watershed groups, will benefit fishes,* especially given the long history of releasing non-native game fish in nearly all state waters and of water diversions for irrigation and cattle use that impede fish passage and alter water flows throughout the region's

waterways. *There are areas within the upper reach of the Escalante River and in portions of the San Juan River where good-quality habitat exists. Prioritizing locations in order to connect stretches of degraded waterways to functioning habitat can augment research and management efforts.*

4.4. Conclusion

GLCA managers need reliable information on current and trending conditions for the natural resources they manage to help them make informed decisions and to take timely actions to sustain healthy, vital ecosystems over time. This is no easy task given the diversity of ecosystem resources and breadth of factors influencing conditions at the park. GLCA's resource condition influences are varied and include rapidly changing driving forces, such as increasing temperatures, more frequent droughts, new non-native plant and animal introductions and expansions, record-breaking number of park visitors, etc. These driving forces often result in resource impacts that may not be fully understood until after the fact and are often beyond the park's direct ability or immediate capacity to influence.

Response strategies developed in the future by park managers and NPS planners can draw upon the science-based resource conditions described in this report. In many cases, management strategies will include multiple responses and/or address management needs for multiple, inter-related ecosystem resources. By design, using the DPSSR framework, NRCA studies seek to deliver reliable resource condition information that GLCA managers can apply to preserve, protect, and restore functional resource conditions in the park.

Literature Cited

Allen, E. B., L. E. Rao, R. J. Steers, A. Bytnerowicz, and M. E. Fenn. 2009. Impacts of atmospheric nitrogen deposition on vegetation and soils in Joshua Tree National Park. Pages 78–100 in R. H. Webb, L. F. Fenstermaker, J. S. Heaton, D. L. Hughson, E. V. McDonald, and D. M. Miller, editors. The Mojave Desert: Ecosystem processes and sustainability. University of Nevada Press, Las Vegas, Nevada. Available at: https://www.fs.usda.gov/treesearch/pubs/37082 (accessed 16 August 2020).

Andrews, K. M., J. W. Gibbons, and D. M. Jochimsen. 2006. Literature synthesis of the effects of roads and vehicles on amphibians and reptiles. Federal Highway Administration, U.S. Department of Transportation, Report No. FHWA-HEP-08-005. Washington, D.C. Available at: https://www.researchgate.net/publication/228731156_Literature_Synthesis_of_the_Effects_of_Roads_and_Vehicles_on_Amphibians_and_Reptiles (accessed 18 September 2020).

Andrews, C. J., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019. Describing trends in past and future soil moisture in the desert sand shrubland ecosystem in the Bullfrog Region of Glen Canyon National Recreation Area. National Park Service Natural Resource Report NPS/GLCA/NRR—2019/1997. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2266293 (accessed 17 November 2020).

Arizona Daily Sun. 2020. Wandering salamander baffles scientists. Available at: https://azdailysun.com/news/local/wandering-salamander-baffles-scientists/article_33c8dede-7f1c-5c04-8085-2526c699becb.html#:~:text=Last%20week%2C%20volunteers%20doing%20restoration%20work%20on%20the,Lees%20Ferry%20found%20an%20almost%20foot-long%20tiger%20salamander. (accessed 27 October 2020).

Arizona Department of Environmental Quality (ADEQ). 2020. Surface water monitoring and assessment. Available at: http://www.azdeq.gov/programs/water-quality-programs/surface-water-monitoring-and-assessment (accessed 18 September 2020).

Arizona Game and Fish Department (AZGFD). 2012. Arizona's State Wildlife Action Plan: 2012–2022. Arizona Game and Fish Department, Phoenix, Arizona. Available at: https://www.azgfd.com/wildlife/actionplan/ (accessed 5 October 2020).

Arizona Game and Fish Department (AZFGD). 2019. Glen Canyon National Recreation Area trip reports: 2006–2008, 2012–2015, and 2019. Unpublished reports.

Arizona Water Quality Division (AWQD). 2017. 2016 Clean Water Act assessment (July 1, 2010 to June 30, 2015: Arizona's integrated 305(b) assessment and 303(d) listing report. Available at: https://static.azdeq.gov/wqd/wqa/2016_cwaa_final.pdf (accessed 19 November 2020).

Arizona Water Quality Division (AWQD). 2018. Arizona's 2018 303(d) list of impaired waters. Available at: https://static.azdeq.gov/pn/pn_303d_2018draft.pdf (accessed 19 November 2020).

Banner, Roger E. 1992. Physiographic Provinces and surface geology of Utah. Rangelands 14(2): 106–108. Available at: https://journals.uair.arizona.edu/index.php/rangelands/article/viewFile/11074/10347 (accessed 15 August 2020).

Baron, J. S., T. LaFrancois, and B. C. Kondratieff. 1998. Chemical and biological characteristics of desert rock pools in intermittent streams of Capitol Reef National Park, Utah. Great Basin Naturalist 58: 250–264. Available at: https://scholarsarchive.byu.edu/cgi/viewcontent.cgi?article=3154&context=gbn (accessed 20 April 2020).

Barrett, W. G., G. M. VanDyne, and E. P. Odum. 1976. Stress ecology. BioScience 26: 192–194.

Berghoff, K. 1995. Capitol Reef National Park tinajas wetland survey summary report, April 1995. Resource Management and Science Division, Capitol Reef National Park.

Bezzerides, N. and K. Bestgen. 2002. Status review of roundtail chub *Gila robusta*, flannelmouth sucker *Catostomus latipinnis*, and bluehead sucker *Catostomus discobolus* in the Colorado River Basin. Colorado State University. Available at: https://www.researchgate.net/publication/316043511_STATUS_REVIEW_OF_ROUNDTAIL_CHUB_Gila_robusta_FLANNELMOUTH_SUCKER_Catostomus_latipinnis_AND_BLUEHEAD_SUCKER_Catostomus_discobolus_IN_THE_COLORADO_RIVER_BASIN (accessed 23 December 2020).

Blaustein, A. R., S. C. Walls, B. A. Bancroft, J. J. Lawler, C. L. Searle, and S. S. Gervasi. 2010. Direct and indirect effects of climate change on amphibian populations. Diversity 2:281–313. Available at: https://www.bio.purdue.edu/lab/searle/docs/publications/Blaustein%20et%20al.%202010-%20Diversity.pdf (accessed 18 September 2020).

Bloomberg Law. 2020. Navajo, battling Covid, say coal mines sapped drinking water. Environment & Energy Report, 17 June 2020. Available at: https://news.bloomberglaw.com/environment-and-energy/virus-ravaged-navajo-say-coal-mines-sapped-their-drinking-water (28 December 2020).

Borthwick, S. 1993. Capitol Reef National Park tinajas wetlands survey proposal. National Park Service (NPS). Available at: https://irma.nps.gov/DataStore/Reference/Profile/2174469 (accessed 12 November 2020).

Bower, M. R. and W. A. Hubert. 2008. Habitat features affect bluehead sucker, flannelmouth sucker, and roundtail chub across a headwater tributary system in the Colorado River Basin. Journal of Freshwater Ecology 23: 347–357.

Brasher, A. M. D., C. M. Albano, R. N. Close, M. L. Freeman, C. L. Lauver, S. A. Monroe, S. E. Stumpf, A. E. C. Snyder, and L. P. Thomas. 2011. Aquatic macroinvertebrate monitoring protocol for the Southern Colorado Plateau Network. Natural Resource Report

NPS/SCPN/NRR—2011/460. National Park Service, Fort Collins, Colorado. Available at: https://irma.nps.gov/DataStore/DownloadFile/436618 (accessed 28 October 2020).

Brooks, M. L. 2003. Effects of increased soil nitrogen on the dominance of alien annual plants in the Mojave Desert. Journal of Applied Ecology. 40:344–353.

Brown, B. T. and R. R. Johnson. 1983. The distribution of bedrock depressions (tinajas) as sources of surface water in Organ Pipe Cactus National Monument, Arizona. Journal of the Arizona-Nevada Academy of Science 18: 61–68. Available at: https://www.jstor.org/stable/27641690?seq=1#metadata_info_tab_contents (accessed 9 November 2020).

Bryce, S. A., J. R. Strittholt, B. C. Ward, and D. M. Bachelet. 2012. Colorado Plateau Rapid Ecoregional Assessment Report. Prepared for the U.S. Department of the Interior, Bureau of Land Management, Denver, Colorado. Available at: https://landscape.blm.gov/REA_General_Docs/COP_Final_Report_Body.pdf (accessed 30 March 2020).

Bureau of Land Management (BLM). 2015. Analysis of the management situation. Livestock grazing plan amendment, environmental impact statement. U.S. Department of Interior. Available at: https://eplanning.blm.gov/public_projects/lup/69026/89782/107364/201507_GSENM_AMS_Final_508.pdf (accessed 18 September 2020).

Bureau of Reclamation. 2020. Colorado River Basin natural flow and salt data. Available at: https://www.usbr.gov/lc/region/g4000/NaturalFlow/documentation.html (accessed 14 December 2020).

Bureau of Reclamation. 2021. Upper Colorado Region: Glen Canyon Dam. Available at: https://www.usbr.gov/uc/water/crsp/cs/gcd.html#:~:text=The%20end%20of%20December%20elevation,the%20driest%20periods%20on%20record (accessed 8 February 2021).

Burghardt, J. E., E. S. Norby, and H. S. Pranger II. 2014. Abandoned mineral lands in the National Park System-comprehensive inventory and assessment. Natural Resource Technical Report NPS/NRSS/GRD/NRTR–2014/906. National Park Service, Fort Collins, Colorado. Available at: https://www.nps.gov/subjects/abandonedmineralland s/publications.htm (accessed 21 October 2020).

Butterfield, B. J., R. S. Anderson, C. A. Holmgren, and J. L. Betancourt. 2019. Extinction debt and delayed colonization have had comparable but unique effects on plant community-climate lags since the Last Glacial Maximum. Global Ecology and Biogeography 28: 1067–1077. Available at: https://ecoss.nau.edu/wp-content/uploads/2019/07/Butterfield-et-al.-2019-Global-Ecology-and-Biogeography.pdf (accessed 14 December 2020).

Cartwright, J. M., K. A. Dwire, Z. Freed, S. J. Hammer, B. McLaughlin, L. W. Misztal, E. R. Schenk, J. R. Spence, A. E. Springer, and L. E. Stevens. 2020. Oases of the future? Springs as

potential hydrologic refugia in drying climates. Frontiers in Ecology and Environment 18: 245–253. Available at: https://esajournals.onlinelibrary.wiley.com/doi/full/10.1002/fee.2191 (accessed 22 October 2020).

Cathcart, C. N., C. A. Pennock, C. A. Cheek, M. C. McKinstry, P. D. MacKinnon, M. M. Conner, and K. B. Gido. 2018. Waterfall formation at a desert river-reservoir delta isolates endangered fishes. River Research and Applications 34: 948–956.

Chan, M. A., K. Moser, J. M. Davis, G. Southam, K. Hughes, and T. Graham. 2005. Desert potholes: ephemeral aquatic microsystems. Aquatic Geochemistry 11: 279–302. Available at: https://link.springer.com/article/10.1007/s10498-004-6274-8 (accessed 9 November 2020).

Christiana, D. 1991. Hydrology and water resources of Capitol Reef National Park, Utah: with emphasis on the Middle Fremont River area. Master's Thesis. University of Arizona. Available at: https://repository.arizona.edu/handle/10150/192054 (accessed 9 November 2020).

Coles, J., D. Clark, M. Dela Cruz, T. Clark, S. Topp, A. Evenden, A. Wight, G. Wakefield, and J. Von Loh. 2009. Vegetation classification and mapping project report, Capitol Reef National Park. Natural Resource Technical Report NPS/NCPN/NRTR—2009/187. National Park Service, Fort Collins, Colorado. Available at: https://pubs.etic.nps.gov/eTIC/CACO-CHIS/CARE_158_D257_0001_of_0882.pdf (accessed 12 November 2020).

Collins, J. P. and A. Storfer. 2003. Global amphibian declines: sorting the hypotheses. Diversity and Distributions 9: 89–98. Available at: https://onlinelibrary.wiley.com/doi/epdf/10.1046/j.1472-4642.2003.00012.x (accessed 18 September 2020).

Conservation Biology Institute (CBI). 2015. Aquatic intactness, Utah and the Colorado Plateau. Available at: https://databasin.org/maps/2e6d671d25414d47b2e21072665eefb1 (accessed 19 November 2020).

Conservation Biology Institute (CBI). 2020. Bureau of Land Management (BLM) Grazing Allotments in Utah (Last modified 14 May 2011). Available at: https://databasin.org/datasets/1397068f2d6d4241962b2135ec137494 (accessed 5 October 2010).

Conservation Measures Partnership. 2016. Classification of conservation actions and threats. Available at: https://www.conservationmeasures.org/ (accessed 10 October 2020).

Cooley, M. E. 1965. Stratigraphic sections and records of springs in the Glen Canyon region of Utah and Arizona. Museum of Northern Arizona. Flagstaff, Arizona. Available at: https://irma.nps.gov/DataStore/Reference/Profile/119228 (accessed 27 October 2020).

Craig, K. A. and C. A. Pinnock. 1995. Monitoring the northern leopard frog population at river mile −9.0 on Colorado River below Glen Canyon Dam. Interim Report. Resource Management Division. Glen Canyon National Recreation Area.

Cullinane Thomas, C., and L. Koontz. 2020. 2019 national park visitor spending effects: Economic contributions to local communities, states, and the nation. Natural Resource Report NPS/NRSS/EQD/NRR—2020/2110. National Park Service, Fort Collins, Colorado. Available at: https://www.nps.gov/subjects/socialscience/vse.htm (accessed 9 September 2020).

Davis, J. M. 2013. Physical, chemical, and biological characteristics of weathering pits, Moab, Utah. Dissertation. University of Utah, Salt Lake City, Utah.

Davis, J. A., A. Kerezsy, and S. Nicol. 2017. Springs: conserving perennial water is critical in arid landscapes. Biological Conservation 211: 30–35. Available at: https://www.researchgate.net/publication/312185891_Springs_Conserving_perennial_water_is_critical_in_arid_landscapes (accessed 21 October 2020).

Davis, P. A., M. I. Staid, J. B. Plescia, and J. R. Johnson. 2002. Evaluation of airborne image data for mapping riparian vegetation with the Grand Canyon. Open-File Report 02-470. U.S. Geological Survey. Available at: https://pdfs.semanticscholar.org/bc31/10cdf8d8999fc7ddafacc3ae827c80a8f5e7.pdf (accessed 6 October 2020).

Day, N. K., T. S. Schmidt, J. J. Roberts, B. C. Osmundson, J. J. Willacker, and C. A. Eagles-Smith. 2020. Mercury and selenium concentrations in fishes of the Upper Colorado River Basin, southwestern United States: a retrospective assessment. PLoS ONE 15: e0226827. Available at: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0226824 (accessed 17 December 2020).

DeCant, J. P. 2008. Russian olive, *Elaeagnus angustifolia*, alters patterns in soil nitrogen pools along the Rio Grande River, New Mexico, USA. Wetlands 28: 896–904.

Drost, C. and M. K. Sogge. 1995. Preliminary survey of leopard frogs in Glen Canyon National Recreation Area. Proceedings of the second biennial conference on research in Colorado Plateau National Parks. 25–28 October 1995: 239–253. National Park Service. Transactions and Proceedings Series. NPS/NRNAU/NRTP-95/11.

Drost, C., L. Gelczis, R. P. O'Donnell, K. Mock, J. Baker, and C. M. Culumber. 2008. Population status and viability of leopard frogs (*Rana pipiens*) in Grand Canyon, Glen Canyon, and Canyonlands. Report to the Bureau of Reclamation, Glen Canyon National Recreation Area, and Grand Canyon National Park as cited in Stortz et al. 2018.

Drost, C. A., R. P. O'Donnell, K. E. Mock, and T. C. Theimer. 2011. Population status and population genetics of northern leopard frogs in Arizona: U.S. Geological Survey Open-File Report 2011–1186. Available at: http://pubs.usgs.gov/of/2011/1186/ (accessed 7 October 2020).

Dyer, M., S. A. Monroe, and S. E. Stumpf. 2016. Water quality monitoring for the Escalante River and Coyote Gulch in Glen Canyon National Recreation Area: 2011–2013 Summary report. Natural Resource Data Series NPS/SCPN/NRDS—2016/1219. National Park Service, Fort

Collins, Colorado. Available at: https://irma.nps.gov/DataStore/DownloadFile/551393 (accessed 16 December 2020).

Dyer, M., S. A. Monroe, and S. E. Stumpf. 2017. Water quality monitoring for the Escalante River and Coyote Gulch in Glen Canyon National Recreation Area: 2014 Summary report. Natural Resource Data Series NPS/ SCPN/NRDS—2017/1134. National Park Service, Fort Collins, Colorado. Available at: https://irma.nps.gov/DataStore/DownloadFile/593211 (accessed 16 December 2020).

Eagles-Smith, C. A., J. J. Willacker, and C. M. Flanagan Pritz. 2014. Mercury in fishes from 21 national parks in the Western United States—Inter and intra-park variation in concentrations and ecological risk: U.S. Geological Survey Open-File Report 2014-1051, 54 p. Available at: http://dx.doi.org/10.3133/ofr20141051 (accessed 23 December 2020).

Eagles-Smith, C. A., J. J. Willacker, S. J. Nelson, C. M. Flanagan Pritz, D. P. Krabbenhoft, C. Y. Chen, J. T. Ackerman, E. H. Campbell Grant, and D. S. Pilliod. 2020. A National-scale assessment of mercury bioaccumulation in United States National Parks using dragonfly larvae as biosentinels through a citizen-science framework. Environmental Science & Technology: 1–12. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2276785 (accessed 16 December 2020).

Escalante River Watershed Partnership (ERWP). 2015. Woody invasive control guidelines: Appendix A of the action plan. Woody invasive control and restoration committee. Escalante River Watershed Partnership. May 2015, 2nd edition. Available at: http://escalanteriverwatershedpartnership.org/wp-content/uploads/2015/04/Woody-Invasive-Control-Plan-V2-Final-1.pdf (accessed 3 December 2020).

Fitzpatrick, M. C. and W. W. Hargrove. 2009. The projection of species distribution models and the problem of non-analog climate. Biodiversity and Conservation, 18(8), 2255. Available at: https://www.srs.fs.usda.gov/pubs/33396 (accessed 9 December 2020).

Fowler, D., J. A. Pyle, J. A. Raven, and M. A. Sutton. 2013. The global nitrogen cycle in the twenty-first century: Introduction. Philosophical Transactions of the Royal Society B: Biological Sciences, 368(1621), 20130165. Available at: http://doi.org/10.1098/rstb.2013.0165 (accessed 16 August 2020).

Fowler, J. F., N. L. Stanton and R. L. Hartman. 2007. Distribution of hanging garden vegetation associations on the Colorado Plateau, USA. Journal of the Botanical Research Institute of Texas 1: 585–607. Available at: https://www.fs.fed.us/rm/pubs_other/rmrs_2007_fowler_j002.pdf (accessed 5 January 2020).

Frier, W. P., R. C. Byles, and R. M. Stewart. 2018. Vegetation change mapping standard operating procedure. Glen Canyon Ecological Forecasting Team, NASA DEVELOP LaRC Summer 2018.

Gido, K. B. and D. L. Propst. 2012. Long-term dynamics of native and nonnative fishes in the San Juan River, New Mexico and Utah, under a partially managed flow regime. Transactions of the American Fisheries Society 141: 645–659.

Gladney, E. S., T. Graham, R. W. Ferenbaugh, M. G. Bell, C. Burns, J. D. Morgan, and E. J. Nickell. 1993. Chemical analysis of selected pothole water sources in southwestern national parks, monuments, and recreation areas. Los Alamos National Laboratory.

Glen Canyon Institute. 2017. The evolution of the Colorado Plateau and Colorado River. Available at: https://medium.com/river-talk/the-evolution-of-the-colorado-plateau-and-colorado-river-ac159791b73c (accessed 4 May 2021).

Glen Canyon National Recreation Area Act. 1972. Establishment, Public Law 92-593.

Gloss, S. P., J. E. Lovich, and T. S. Melis. 2005. The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282. Available at: https://pubs.usgs.gov/circ/1282/ (accessed 30 September 2020).

Gonzales, P. 2013. Climate change trends and vulnerability of the Colorado River and Glen Canyon National Recreation Area. Natural Resource Stewardship and Science, National Park Service, Washington, DC. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2217878 (accessed 10 December 2020).

Graham, J. P. 2016. Glen Canyon National Recreation Area: Geologic Resources Inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2016/1264. National Park Service, Fort Collins, Colorado. Available at: http://www.npshistory.com/publications/glca/nrr-2016-1264.pdf (accessed 9 November 2020).

Grand Canyon Wildlands Council (GCWC). 2002. Inventory of 100 Arizona Strip springs, seeps and natural ponds: final project report. Grand Canyon Wildlands Council, Flagstaff, Arizona. Available at: http://docs.springstewardship.org/PDF/ASSP_Final_Report020430.pdf (accessed 28 July 2002).

Gremer, J. R., C. Andrews, J. R. Norris, L. P. Thomas, S. M. Munson, M. C. Duniway, and J. B. Bradford. 2018. Increasing temperature seasonality may overwhelm shifts in soil moisture to favor shrub over grass dominance in Colorado Plateau drylands. *Oecologia*, *188*(4), 1195–1207. Available at: https://www.nps.gov/im/scpn/other-documents.htm (accessed 10 December 2020).

Haefner, J. W. and A. M. Lindahl. 1991. The ecology of small pools in Capitol Reef National Park, UT: Phase II, Final Report. Department of Biology and Ecology Center, Utah State University. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2174476 (accessed 12 November 2020).

Hand, F. E. 1979. Ground water resources in the northern part of the Glen Canyon National Recreation Area and adjacent lands west of the Colorado and Green Rivers, Utah. Master's Thesis. University of Wyoming. Laramie, Wyoming as cited in Huntoon 1979.

Harwell, M. A., J. H. Gentile, L. D. McKinney, J. W. Tunnell Jr., W. C. Dennison, R. H. Kelsey, K. M. Stanzel, G. W. Stunz, Ki. Withers, and J. Tunnell. 2019. Conceptual framework for assessing ecosystem health. Available at: https://www.sportfishcenter.org/sites/default/files/2020-01/Harwell_et_al._2019.pdf (accessed 17 November 2020).

Heil K. D., J. M. Porter, and W. H. Romme. 1993. Vascular flora and vegetation of Capitol Reef National Park, Utah. NRTR-93-01. Cooperative Park Studies Unit at Northern Arizona University, Flagstaff, AZ. Available at: https://irma.nps.gov/DataStore/DownloadFile/469946 (accessed 2 December 2020).

Hill, M. E., and T. Ayers. 2009. Vascular plant inventory of Glen Canyon National Recreation Area. Natural Resource Technical Report NPS/SCPN/NRTR—2009/264. National Park Service, Fort Collins, Colorado. Available at: https://irma.nps.gov/DataStore/Reference/Profile/663146 (accessed 17 November 2020).

Hines, B. 2018. Nonnative and rare fish monitoring in the lower San Juan River 2018. Utah Division of Wildlife Resources.

Holden, P. B. 1999. Flow recommendations for the San Juan River. San Juan River Basin Recovery Implementation Program, U.S. Fish and Wildlife Service, Albuquerque, New Mexico. Available at: https://www.fws.gov/southwest/SJRRIP/pdf/SJW2/Holden_(1999)_San_Juan_River_Flow_Recommendations.pdf (accessed 15 December 2020).

Holden, P. B. and J. R. Irvine. 1975. Ecological survey and analysis of the aquatic and riparian fauna and flora of Escalante Canyon, Utah. Contract No. CS 12004 B034, Final report to National Park Service and Cooperative Research Unit, Utah State University, Logan, Utah.

Huntoon, P. W. 1979. The feasibility of developing ground water supplies in and adjacent to the Glen Canyon National Recreation Area and Canyonlands National Park west of the Colorado and Green Rivers, Utah. Wyoming Water Research Institute. Laramie, WY. Available at: http://www.riversimulator.org/Resources/NPS/Canyonlands/GroundwaterDevelopmentFeasibility1979.pdf (accessed 27 October 2020).

Inouye, R. S. 2006. Effects of shrub removal and nitrogen addition on soil moisture in sagebrush steppe. Journal of Arid Environments. 65: 604–618.

Intergovernmental Panel on Climate Change (IPCC). 2014. Synthesis report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R. K. Pachauri and L. A. Meyer (eds.)]. IPCC, Geneva, Switzerland. Available at: https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf (accessed 10 December 2020).

Jackson, S. K. 2015. Effects of ecological restoration techniques in Glen Canyon National Recreation Area. Master's Thesis. University of Nevada, Las Vegas, Nevada. Available at: https://digitalscholarship.unlv.edu/cgi/viewcontent.cgi?article=4623&context=thesesdissertations (accessed 3 November 2020).

Jeong, S. G., Y. Mo, H. G. Kim, C. H. Park, and D. K. Lee. 2016. Mapping riparian habitat using a combination of remote-sensing techniques. International Journal of Remote Sensing 37: 1069–1088. Available at: https://www.tandfonline.com/doi/full/10.1080/01431161.2016.1142685 (accessed 1 December 2020).

Johnson, M. L. and R. Speare. 2005. Possible modes of dissemination of the amphibian chytrid *Batrachochytrium dendrobatidis* in the environment. Diseases and aquatic organisms. 65: 181–186. Available at: https://www.int-res.com/articles/dao2005/65/d065p181.pdf (accessed 8 February 2021).

Jones, K. B., C. E. Edmonds, E. T. Slonecker, J. D. Wickham, A. C. Neale, T. C. Wade, K. H. Riitters, and W. G. Kepner. 2008. Detecting changes in riparian habitat conditions based on patterns of greenness change: A case study from the Upper San Pedro River Basin, USA. Ecological Indicators. 8: 89–99. Available at: https://www.sciencedirect.com/science/article/abs/pii/S1470160X07000039 (accessed 1 December 2020).

Jocque, M., B. Vanschoenwinkel, and L. Brendonck. 2010. Freshwater rock pools: a review of habitat characteristics, faunal diversity and conservation value. Freshwater Biology 55: 1587–1602. Available at: https://onlinelibrary.wiley.com/doi/epdf/10.1111/j.1365-2427.2010.02402.x (accessed 29 March 2021).

Katz, G. L., G. M. Tuttle, M. W. Denslow, and A. P. Norton. 2020. Legacy effects of Russian olive (*Elaeagnus angustifolia* L.) in a riparian ecosystem three years post-removal. Wetlands 40: 1897–1907. (not available online)

Kodric-Brown, A. and J. H. Brown. 2007. Native fishes, exotic mammals, and the conservation of desert springs. Frontiers in Ecology and the Environment 5:549–553. Available at: https://esajournals.onlinelibrary.wiley.com/doi/epdf/10.1890/070002 (accessed 29 October 2020).

Lamarra, V. and D. Lamarra. 2018. San Juan River habitat monitoring: 2017. Annual report submitted to San Juan River Biological Committee. U.S. Fish and Wildlife Service. Available at: https://www.fws.gov/southwest/sjrip/pdf/Habitat%20monitoring%20-%202017.pdf (accessed 23 December 2020).

Landers, D., S. Simonich, D. Jaffe, L. Geiser, D. Campbell, A. Schwindt, C. Schreck, M. Kent, W. Hafner, H. Taylor, K. Hageman, S. Usenko, L. Ackerman, J. Schrlau, N. Rose, T. Blett, M. Erway. 2010. The fate, transport, and ecological impacts of airborne contaminants in western national parks (USA). U.S. Environmental Protection Agency, Office of Research and

Development, NHEERL, Western Ecology Division, Corvallis, Oregon. Available at: https://pubs.acs.org/doi/pdf/10.1021/es901866e (accessed 1 April 2021).

Laub, B. G., G. P. Theide, W. W. Macfarlane, and P. Budy. 2018. Evaluating the conservation potential of tributaries for native fishes in the Upper Colorado River Basin. Fisheries 43: 194–206. Available at: https://afspubs.onlinelibrary.wiley.com/doi/epdf/10.1002/fsh.10054 (accessed 15 December 2020).

Los Angeles Times. 2020. Coal plants are closing across the West. Here are the companies sticking with coal. Climate and Environment section, 4 February 2020. Available at: https://www.latimes.com/environment/story/2020-02-04/coal-power-plants-western-us (accessed 28 December 2020).

Lukas, J. and E. Payton. 2020. Colorado River Basin climate and hydrology: State of the science. Western Water Assessment, University of Colorado, Boulder. Available at: https://scholar.colorado.edu/concern/reports/8w32r663z (accessed 10 December 2020).

Lustgarten, A. 2015. Navajo Generating Station Powers and Paralyzes the Western U.S. Scientific American newsletter. Available at: https://www.scientificamerican.com/article/navajo-generating-station-powers-and-paralyzes-the-western-u-s/ (accessed 28 December 2020).

Maheu-Giroux, M. and S. de Blois. 2005. Mapping the invasive species *Phragmites australis* in linear wetland corridors. Aquatic Botany 83: 310–320.

Maupin, M.A., T. Ivahnenko, B. Bruce. 2018. Estimates of water use and trends in the Colorado River Basin, Southwestern United States, 1985–2010: U.S. Geological Survey Scientific Investigations Report 2018–5049. Available at: https://doi.org/10.3133/sir20185049 (accessed 22 October 2020).

Macfarlane, W. W., J. T. Gilbert, M. L. Jensen, J. D. Gilbert, N. Hough-Snee, P. A. McHugh, J. M. Wheaton, and S. N. Bennett. 2017. Riparian vegetation as an indicator of riparian condition: Detecting departures from historic condition across the North American West. Journal of Environmental Management. 202: 447–460. Available at: https://landfire.gov/documents/Macfarlane2016JEM.pdf (accessed 28 March 2021).

McAda, C. W., C. Philips, C. R. Berry Sr., and R. S. Wydoski. 1977. A survey of threatened and endangered fish in southeastern Utah streams. Final report. Utah Division of Wildlife Resources, Salt Lake City. Utah Cooperative Fish Resources Unit, Utah State University, Logan, Utah as cited in Mueller et al. (1999).

McGwire. K. C. 2019. Optimized stratification for mapping riparian vegetation in arid and semiarid environments. Remote Sensing 11: 1638. Available at: https://www.mdpi.com/2072-4292/11/14/1638 (accessed 1 December 2020).

McIntyre, C., K. Gallo, E. Gwilliam, J. A. Hubbard, J. Christian K. Bonebrake, G. Goodrum, M. Podolinsky, L. Palacios, B. Cooper and M. Isley. 2018. Springs, seeps, and tinajas monitoring

protocol: Chihuahuan and Sonoran Desert Networks. Natural Resource Report NPS/CHDN/NRR—2018/1796. National Park Service, Fort Collins, Colorado. Available at: http://www.npshistory.com/publications/nr-reports/nrr-2018-1796.pdf (accessed 12 November 2020).

McIvor, C. and M. Thieme. 1999. Flannelmouth suckers: movement in the Glen Canyon reach and spawning in the Paria River. Geophysical Monograph Series, January: 289–298. Available at: https://www.researchgate.net/publication/291356483_Flannelmouth_Suckers_Movement_in_the_Glen_Canyon_Reach_and_Spawning_in_the_Paria_River (accessed 17 December 2020).

McPhaden, M. J., A. Santoso, and W. Cai (editors). 2021. El Niño Southern Oscillation in a changing climate. American Geophysical Union and John Wiley and Sons, Inc. Available at: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/9781119548164 (accessed 7 January 2021).

Miller, M. P. and A. M. D. Brasher. 2011. Differences in macroinvertebrate community structure in streams and rivers with different hydrologic regimes in the semi-arid Colorado Plateau. River Systems 19: 225–238. Available at: https://digitalcommons.usu.edu/crc_research/413/ (accessed 16 December 2020).

Miller, D. A. W., E. H. Campbell Grant, E. Muths, S. M. Amburgey, M. J. Adams, M. B. Joseph, J. H. Waddle, P. T. J. Johnson, M. E. Ryan, B. R. Schmidt, D. L. Calhoun, C. L. Davis, R. N. Fisher, D. M. Green, B. R. Hossack, T. A. G. Rittenhouse, S. C. Walls, L. L. Bailey, S. S. Cruickshank, G. M. Fellers, T. A. Gorman, C. A. Haas, W. Hughson, D. S. Pillod, S. J. Price, A. M. Ray, W. Sadinski, S. Saenz, W. J. Barichivich, A. Brand, C. S. Brehme, R. Dagit, K. S. Delaney, B. M. Glorioso, L. B. Kats, P. M. Kleeman, C. A. Pearl, C. J. Rochester, S. P. D. Riley, M. Roth, and B. H. Sigafus. 2018. Quantifying climate sensitivity and climate-driven change in North American amphibian communities. Nature Communications 9. Available at: https://doi.org/10.1038/s41467-018-06157-6 (accessed 18 September 2020).

Miller, S. and S. Judson. 2011. Macroinvertebrate sample processing and reporting methodologies of the National Aquatic Monitoring Center. Department of Watershed Sciences, Utah State University. Available at: https://www.usu.edu/buglab/Content/Metadata_accompanyingPDF2.pdf (access 16 December 2020).

Mifsud, D. A. 2014. A status assessment and review of the herpetofauna within the Saginaw Bay of Lake Huron. Journal of Great Lakes Research 40: 183–191. Available at: https://www.sciencedirect.com/science/article/pii/S0380133013001421 (accessed 1 October 2020).

Mineau, M., D. V. Baxter, and A. M. Marcarelli. 2011. A non-native riparian tree (*Elaeagnus angustifolia*) changes nutrient dynamics in streams. Ecosystems 14: 353–365. Available at: https://link.springer.com/article/10.1007/s10021-011-9415-0 (accessed 21 December 2020).

Monahan, W. B. and N. A. Fisichelli. 2014. Recent climate change exposure of Glen Canyon National Recreation Area. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2212631 (accessed 24 June 2020).

Monahan, W. B., J. E. Gross, L. K. Svancara, and T. Philippi. 2012. A guide to interpreting NPScape data and analyses. Natural Resource Technical Report NPS/NRSS/NRTR—2012/578. National Park Service, Fort Collins, Colorado. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2184927 (accessed August 18, 2020).

Morrison, R. R., M. C. Stone, and D. W. Sada. 2013. Environmental response of a desert springbrook to incremental discharge reductions, Death Valley National Park, California, USA. Journal of Arid Environments 99: 5–13.

Mueller, G., L. Boobar, R. Wydoski, K. Comella, R. Fridell, and Q. Bradwisch. 1999. Aquatic survey of the lower Escalante River, Glen Canyon National Recreation Area, Utah, June 22–26, 1998. U.S. Geological Survey. Available at: https://pubs.er.usgs.gov/publication/ofr99101 (accessed 15 July 2020).

Muths, E., A. L. Gallant, E. H. Campbell Grant, W. A. Battaglin, D. E. Green, J. S. Staiger, S. C. Walls, M. S. Gunzburger, and R. F. Kearney. 2006. The Amphibian Research and Monitoring Initiative (ARMI): 5-Year Report: U.S. Geological Survey Scientific Investigations Report 2006–5224, 77 p. Available at: https://pubs.usgs.gov/sir/2006/5224/report.pdf (accessed 9 July 2020).

National Drought Mitigation Center. 2021. U.S. drought monitor map, June 15, 2021. Available at: https://droughtmonitor.unl.edu/CurrentMap.aspx (accessed 17 June 2021).

National Park Service (NPS). No Date. Resource Stewardship Strategy development guide. Version 3.0. (not available online)

National Park Service (NPS). 2010. National Park Service Climate Change Response Strategy. National Park Service Climate Change Response Program, Fort Collins, Colorado. Available at: https://www.nps.gov/subjects/climatechange/upload/NPS_CCRS-508compliant.pdf (accessed 10 December 2020).

National Park Service (NPS). 2013. State of the Park report for Organ Pipe Cactus National Monument. State of the Park Series No. 3. National Park Service, Washington, D.C. Available at: http://npshistory.com/publications/state-of-the-park/orpi-2013.pdf (accessed 12 November 2020).

National Park Service (NPS). 2014. Foundation document, Glen Canyon National Recreation Area and Rainbow Bridge National Monument. National Park Service.

National Park Service (NPS). 2015. Hydrologic activity, Glen Canyon Dam. Available at: https://www.nps.gov/glca/learn/nature/hydrologicactivity.htm (accessed 15 August 2020).

National Park Service (NPS). 2018. Frequently asked questions. Available at: https://www.nps.gov/glca/faqs.htm (accessed 18 August 2020).

National Park Service (NPS). 2020a. Hydrographic and impairment statistics: Glen Canyon National Recreation Area. Available at: https://www.nps.gov/subjects/protectingwater/his-parkreport.htm?unitType=Park&parkNames=GLCA (accessed 25 November 2020).

National Park Service (NPS). 2020b. Endangered fish. Available at: https://www.nps.gov/glca/learn/nature/endangeredfish.htm (accessed 15 July 2020).

National Park Service (NPS) Air Resources Division (ARD). 2010. Air quality in national parks: 2009 annual performance and progress report. Natural Resource Report NPS/NRPC/ARD/NRR—2010/266. National Park Service, Denver, Colorado. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2166247 (accessed 2 February 2020).

National Park Service (NPS) Air Resources Division (ARD). 2020. Air trends, Glen Canyon National Recreation Area. Available at: https://www.nps.gov/subjects/air/park-conditions-trends.htm?tabName=summary&parkCode=GLCA&paramCode=Overall%20Air%20Quality&startYr=2009&endYr=2018&monitoringSite=CANY1%20(IMPROVE)&timePeriod=Summary (accessed 4 November 2020).

National Park Service (NPS) Visitor Use Statistics (VUS). 2020a. Glen Canyon NRA annual park recreation visits with graph (1964–2019). Available at: https://irma.nps.gov/STATS/SSRSReports/Park%20Specific%20Reports/Annual%20Park%20Recreation%20Visitation%20Graph%20(1904%20-%20Last%20Calendar%20Year)?Park=GLCA (accessed 4 November 2020).

National Park Service (NPS) Visitor Use Statistics (VUS). 2020b. Glen Canyon NRA annual summary by month and district. Available at: https://irma.nps.gov/STATS/SSRSReports/Park%20Specific%20Reports/Park%20All%20Months?Park=GLCA (accessed 4 November 2020).

National Park Service (NPS) Visitor Use Statistics (VUS). 2020c. Glen Canyon NRA traffic counts by location. Available at: https://irma.nps.gov/STATS/SSRSReports/Park%20Specific%20Reports/Traffic%20Counts?Park=GLCA (accessed 4 November 2020).

National Parks Conservation Association (NPCA). 2019. Polluted parks, how America is failing to protect our national parks, people and planet from air pollution. Available at: https://npca.s3.amazonaws.com/documents/NPCAParksReport2019.pdf (accessed 22 July 2020).

NatureServe. 2020a. Terrestrial ecological system: Colorado Plateau hanging garden. Available at: https://explorer.natureserve.org/Taxon/ELEMENT_GLOBAL.2.722908/Colorado_Plateau_Hanging_Garden (accessed 21 October 2020).

NatureServe. 2020b. Online database. Available at: https://explorer.natureserve.org/ (accessed 18 September 2020).

Neff, J. C., R. L. Reynolds, J. Belnap, and P. Lamothe. 2005. Multi-decadal impacts of grazing on soil physical and biogeochemical properties in southeast Utah. Ecological Applications 15: 87–95. Available at: https://www.researchgate.net/publication/42854828_Multi-Decadal_Impacts_of_Grazing_on_Soil_Physical_and_Biogeochemical_Properties_in_Southeast_Utah (accessed 15 November 2020).

Nethoff, D. I., B. J. Cooper, and R. R. Shroba. 1995. Giant sandstone weathering pits near Cookie Jar Butte, Southeastern Utah. Pages 25–39 *in* van Riper, C. III, editor. Proceedings of the second biennial conference on research in Colorado Plateau National Parks, 25–28 October 1993. National Park Service. Transactions and Proceedings Series. NPS/NRNAU/NRTP-95/11.

Nguyen, U., E. Glenn, P. Nagler, and R. Scott. 2014. Long-term decrease in satellite vegetation indices in response to environmental variables in an iconic desert riparian ecosystem: The Upper San Pedro, Arizona, USA. Ecohydrology DOI: 10.1002/eco.1529. Available at: https://pubs.er.usgs.gov/publication/70125289 (accessed 1 December 2020).

Nowak, E. M. and T. B. Persons. 2008. Inventory of amphibians and reptiles for twelve National Parks in the Southern Colorado Plateau Network. Final report to the National Park Service, Southern Colorado Plateau Network, Flagstaff, Arizona. Available at: https://irma.nps.gov/DataStore/DownloadFile/609002 (accessed 18 September 2020).

NPSpecies. 2020. The National Park Service biodiversity database. Available at: https://irma.nps.gov/NPSpecies/Search/SpeciesList (accessed 20 April 2020).

O'Donnell, R. P. and K. Mock. 2008. Patterns of genetic diversity and divergence in northern leopard frogs (*Rana pipiens*) in the Glen Canyon and Canyonlands regions of southern Utah and northern Arizona. Final Report. Department of Biology and the Ecology Center, Wildland Resources Department, Utah State University. Logan, Utah. Available at: https://www.researchgate.net/publication/237591480_Patterns_of_Genetic_Diversity_and_Divergence_in_Northern_Leopard_Frogs_Rana_pipiens_in_the_Glen_Canyon_and_Canyonlands_Regions_of_Southern_Utah_and_Northern_Arizona (accessed 1 October 2020).

O'Driscoll, M., D. DeWalle, C. Humphrey Jr., and G. Iverson. 2019. Groundwater seeps: portholes to evaluate groundwater's influence on stream water quality. Journal of Contemporary Water Research & Education 66: 57–78. Available at: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1936-704X.2019.03302.x (accessed 28 October 2020).

Office of National Marine Sanctuaries. 2020. National Oceanic and Atmospheric Administration (NOAA) National Marine Sanctuaries condition reports. Available at: https://sanctuaries.noaa.gov/science/condition/ (accessed 9 December 2020).

Paroz, Y. M., D. L. Propst, S. M. Carman, and N. Zymonas. 2007. Small-bodied fishes monitoring, San Juan River, September–October 2006. San Juan River Basin Recovery Implementation Program. U.S. Fish and Wildlife Service, Region 2, Albuquerque, New Mexico.

Paroz, Y. M., D. L. Propst, S. M. Carman, and N. Zymonas. 2008. Small-bodied fishes monitoring, San Juan River, September–October 2007. San Juan River Basin Recovery Implementation Program. U.S. Fish and Wildlife Service, Region 2, Albuquerque, New Mexico.

Patten, D. T., L. Rouse, and J. C. Stromberg. 2008. Isolated spring wetlands in the Great Basin and Mojave Deserts, USA: potential response of vegetation to groundwater withdrawal. Environmental Management 41: 398–413. Available at: https://link.springer.com/article/10.1007/s00267-007-9035-9 (accessed 1 November 2020).

Pennock, C. A. 2019. Movement, habitat use, and early life history of fishes in novel river-reservoir complexes. Dissertation. Division of Biology, College of Arts and Sciences, Kansas State University. Available at: https://krex.k-state.edu/dspace/handle/2097/40206 (accessed 17 December 2020).

Perkins, D. J., B. N. Carlsen, M. Fredstrom, R. H. Miller, C. M. Rofer, G. T. Ruggerone, and C. S. Zimmerman. 1984. The effects of groundwater pumping on natural spring communities in Owens Valley. Pages 515–527 *in* R. E. Warner and K. M. Hendrix, editors. California riparian systems; ecology, conservation, and productive management. University of California Press, Berkeley as cited in Patten et al. 2008.

Perkins, D. W., R. Wissinger, M. Moran, S. Monroe, H. Thomas, L. McCoy, and E. Soles. 2018. Springs Monitoring Protocol Implementation Plan for park units in the Southern Colorado Plateau Network. Natural Resource Report NPS/SCPN/NRR—2018/1771. National Park Service, Fort Collins, Colorado. Available at: https://irma.nps.gov/DataStore/DownloadFile/607320 (accessed 21 October 2020).

Propst, D. L., A. H. Kingsbury, and R. D. Larson. 2004. Small-bodied fish monitoring, San Juan River 1998–2003. San Juan River Basin Recovery Implementation Program. U.S. Fish and Wildlife Service, Region 2, Albuquerque, New Mexico.

Ralston, B. E. 2010. Riparian vegetation response to the March 2008 short-duration, high-flow experiment-implications of timing and frequency of flood disturbance on nonnative plant establishment along the Colorado River below Glen Canyon Dam. United States Geological Survey. Open-File Report 2010-1022. Available at: https://pubs.usgs.gov/of/2010/1022/ (accessed 5 October 2020).

Rao, L. E., E. B. Allen, and T. Meixner. 2010. Risk-based determination of critical nitrogen deposition loads for fire spread in southern California deserts. Ecological Applications: 20:1320–1335. Available at: https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/09-0398.1 (accessed 28 March 2021).

Raymond, K., L. Palacios, C. McIntyre, and E. L. Gwilliam. 2019. Status of climate and water resources at Organ Pipe Cactus National Monument: Water year 2018. Natural Resource Report NPS/SODN/NRR—2019/2029. National Park Service, Fort Collins, Colorado. Available at: https://irma.nps.gov/DataStore/DownloadFile/630099 (accessed 12 November 2020).

Robichaud, A. 2020. An overview of selected emerging outdoor airborne pollutants and air quality issues: the need to reduce uncertainty about environmental and human impacts. Journal of the Air & Waste Management Association 70: 341–378. Available at: https://www.tandfonline.com/doi/full/10.1080/10962247.2020.1723738 (accessed 1 April 2020).

Runyon, A. N., A. R. Carlson, J. Gross, D. J. Lawrence, and G.W. Schuurman. 2020. Repeatable approaches to work with scientific uncertainty and advance climate change adaptation in US national parks. Parks Stewardship Forum 36: 98–104. Available at: https://escholarship.org/uc/psf (accessed 9 December 2020).

Ryden, D. W. 2005. Long term monitoring of sub-adult and adult large-bodied fishes in the San Juan River: 2004. Interim Progress Report. U.S. Fish and Wildlife Service.

Sada, D. W., E. Fleishman, and D. D. Murphy. 2005. Associations among spring-dependent aquatic assemblages and environmental and land use gradients in a Mojave Desert mountain range. Diversity and Distributions 11: 91–99. Available at: https://www.jstor.org/stable/pdf/3246786.pdf?refreqid=excelsior%3A3de2ff41aae0bde60d434e8b331aeb6f (accessed 22 October 2020).

Salt Lake Tribune, The. 2020. The demolition of the largest coal-fired power plant in the Western U.S. brings reflection, hope to the northern Navajo Nation. Story released 19 December 2020. Available at: https://www.msn.com/en-us/news/us/the-demolition-of-the-largest-coal-fired-power-plant-in-the-western-us-brings-reflection-hope-to-the-northern-navajo-nation/ar-BB1c4qsU?ocid=uxbndlbing#image=BB1c4qsU_1|2 (accessed 28 December 2020).

Sather, M. E., S. Mukerjee, L. Smith, J. Mathew, C. Jackson, R. Callison, L. Scrapper, A. Hathcoat, J. Adam, D. Keese, P. Ketcher, R. Brunette, J. Karlstrom, and G. Van der Jagt. 2013. Gaseous oxidized mercury dry deposition measurements in the Four Corners area and eastern Oklahoma, U.S.A. Atmospheric Pollution Research 4: 168–180. Available at: https://reader.elsevier.com/reader/sd/pii/S130910421530386X?token=766828A917F0981C45A5AD7381E7AFC38E6553E53EC7F6E8719DDB09ACC9A18DC1D3F140A31F51FA190B91E262172568 (accessed 18 September 2020).

Schleicher, B. J. 2016. Long term monitoring of sub-adult and adult large-bodied fishes in the San Juan River: 2015. Interim Progress Report. Available at: https://www.fws.gov/southwest/SJRRIP/pdf/DOC_Long_term_monitoring_sub-adult_adult_large-bodied_fishes_SJR_2015.pdf (accessed 21 December 2020).

Schleicher, B. J. and D. W. Ryden. 2013. Long term monitoring of sub-adult and adult large-bodied fishes in the San Juan River: 2012. Interim Progress Report. Available at: https://www.fws.gov/southwest/SJRRIP/pdf/DOC_Long_term_monitoring_sub-adult_adult_large-bodied_fishes_San_Juan_River_2012.pdf (accessed 17 December 2020).

Schwinning, S., B. I. Starr, N. J. Wojcik, M. E. Miller, J. E. Ehleringer, and R. L. Sanford. 2005. Effects of nitrogen deposition on an arid grassland in the Colorado Plateau cold desert.

Rangeland Ecology and Management. 58: 565–574. Available at: https://www.sciencedirect.com/science/article/abs/pii/S155074240550085X (accessed 28 March 2021).

Scott, M. L., E. W. Reynolds, A. M. D. Brasher, A. Caires. 2005. The structure and functioning of riparian and aquatic ecosystems of the Colorado Plateau—conceptual models to inform monitoring. U.S. Geological Survey. Available at: https://www.researchgate.net/publication/242397627 (accessed 28 March 2021).

Scott, M. L., L. V. Reynolds, P. B. Shafroth, and J. R. Spence. 2018. The role of an invasive tree in large-scale riparian vegetation expansion and channel narrowing along a dryland river. Ecohydrology 2018: e1988. Available at: https://onlinelibrary.wiley.com/doi/abs/10.1002/eco.1988 (accessed 26 December 2020).

Shafroth, P. B., C. A. Brown, and D. M. Merritt (eds). 2010. Saltcedar and Russian olive control demonstration act science assessment. U.S. Geological Survey Scientific Investigations Report 2009–5247, 143 p. Available at: https://pubs.usgs.gov/sir/2009/5247/ (accessed 21 December 2020).

Sierra Club. n.d. Navajo Generating Station: Arizona's dirtiest coal plant. Available at: https://content.sierraclub.org/creative-archive/sites/content.sierraclub.org.creative-archive/files/pdfs/100_96_NavajoGeneratingStation_FactSht_07_low.pdf (accessed 28 December 2020).

Simkin, S. M., E. B. Allen, W. D. Bowman, C. M. Clark, J. Belnap, M. L. Brooks, B. S. Cade, S. L. Collins, L. H. Geiser, F. S. Gilliam, S. E. Jovan, L. H. Pardo, B. K. Schulz, C. J. Stevens, K. N. Suding, H. L. Throop, and D. M. Waller. 2016. Conditional vulnerability of plant diversity to atmospheric nitrogen deposition across the United States. PNAS first published March 28, 2016, Available at: https://doi.org/10.1073/pnas.1515241113 (accessed 22 July 2020).

Smith, B. E. and D. A. Keinath. 2007. Northern leopard frog (*Rana pipiens*): a technical conservation assessment. Prepared for the USDA Forest Service, Rocky Mountain Region, Species Conservation Project. Available at: https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5182078.pdf (accessed 1 October 2020).

Snow, N. P. and G. Witmer. 2010. American bullfrogs as invasive species: a review of the introduction, subsequent problems, management options, and future directions. Proceedings of the 24th Vertebrate Pest Conference. University of California, Davis. 24: 86–89. Available at: https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=2284&context=icwdm_usdanwrc (accessed 18 September 2020).

Society for the Study of Amphibians and Reptiles (SSAR). 2020. SSAR North American standard English names database. Available at: https://ssarherps.org/cndb/ (accessed 18 September 2020).

Solder, J. E., B. J. Stolp, V. M. Heilweil, and D. D. Susong. 2016. Characterization of mean transit time at large springs in the Upper Colorado River Basin, USA: a tool for assessing groundwater discharge vulnerability. Hydrogeology Journal 24: 2017–33. Available at: https://link.springer.com/article/10.1007/s10040-016-1440-9 (accessed 21 October 2020).

Sorenson, S. K., P. D. Dileanis, and F. A. Branson. 1991. Soil water and vegetation responses to precipitation and changes in depth to groundwater in Owens Valley, California. USGS Water-Supply Paper 2370-G. U.S. Geological Survey, Reston, Virginia. Available at: https://pubs.usgs.gov/of/1989/0260/report.pdf (accessed 1 November 2020).

Spence, J. R. 1995. Characterization and possible origins of isolated Douglas-fir stands on the Colorado Plateau. Pages 71–82 *in* Waugh, W.J., (ed.) Proceedings of a symposium, September 12–14, 1994. Climate change in the Four Corners and adjacent regions: implications for environmental restoration and land-use planning. U.S. Dept. Energy CONF-940325, Grand Junction, CO.

Spence, J. R. 1996a. The controlled flood of 1996: effects on vegetation and leopard frogs (*Rana pipiens*) at RM-8.8L march, Colorado River, Glen Canyon National Recreation Area. Unpublished report, Resource Management Division, Glen Canyon NRA. 19 pp.

Spence, J. R. 1996b. A survey and classification of the riparian vegetation of selected side canyons of Lake Powell, Glen Canyon National Recreation Area. Unpublished report, Resource Management Division, Glen Canyon NRA. 60 pp.

Spence, J. R. 2001. Climate of the central Colorado Plateau, Utah and Arizona: Characterization and recent trends Pp. 187–203 in Thomas, K. and Van Riper III, C. (eds.). Proceedings of the Fifth Biennial Conference on Research on the Colorado Plateau. U.S. Geological Survey Report Ser. USGSFRESC/COPL/2001/24.

Spence, J. R. 2004. Surveys of springs in the Colorado River drainage in Arches National Park, Canyonlands National Park, Glen Canyon National Recreation Area, and Grand Canyon National Park. Final report to Water Resources Division-WASO. Resource Management Division, Glen Canyon NRA. 515 pp.

Spence, J. R. 2005. Notes on significant collections and additions to the flora of Glen Canyon National Recreation Area, Utah and Arizona, between 1992 and 2004. Western North American Naturalist 65: 103–111. Available at: https://scholarsarchive.byu.edu/cgi/viewcontent.cgi?article=1843&context=wnan (accessed 5 January 2020).

Spence, J. R. 2008. Spring-supported vegetation along the Colorado River on the Colorado Plateau. Floristics, vegetation structure and environment. Pages 185–210 *in* L. E. Stevens, L.E and V. J. Meretsky, editors. Aridland springs of North America: Ecology and conservation. University of Arizona Press, Tucson, Arizona.

Spence, J. R. 2017. Assess resource vulnerability of grazed rangelands to rapid climate change for adaptive management, Glen Canyon National Recreation Area. Final Report for PMIS 160774. Science & Resource Management Division, National Park Service. 94 pp.

Spence, J. R. 2018. Rapid spring survey and assessment protocol. Science & Resource Management Division, Glen Canyon National Recreation Area.

Spence, J. R. and G. Cushing. 2019. Preliminary report on climate change in Glen Canyon: potential impacts to natural resources. Unpublished report, Resource Management Division, Glen Canyon NRA. 26 pp.

Spence, J. R. and N. R. Henderson. 1993. Tinaja and hanging garden vegetation of Capitol Reef National Park, southern Utah, U.S.A. Journal of Arid Environments 24: 21–34. Available at: https://www.sciencedirect.com/science/article/pii/S0140196383710025 (accessed 9 November 2020).

Spence, J. R., C. T. LaRue, and J. D. Grahame. 2011. Birds of Glen Canyon National Recreation Area, Utah and Arizona. Monographs of the Western North American Naturalist 5: 20–70. Available at: https://bioone.org/journals/monographs-of-the-western-north-american-naturalist/volume-5/issue-1/042.005.0102/Birds-of-Glen-Canyon-National-Recreation-Area-Utah-and-Arizona/10.3398/042.005.0102.full (accessed 22 October 2020).

Spence, J. R. and L. Whitman. 2015. The Escalante River Watershed Partnership: Conservation of an endangered ecosystem. Pp. 339–352 In Huenneke, L. F., C. Van Riper III, and K. A. Hays-Gilpin (eds.). Colorado Plateau IV. Science and Management at the Landscape Scale. University of Arizona Press, Tucson, Arizona.

Spring Stewardship Institute. 2020. Springs online: the springs and springs-dependent species database. Available at: http://springsdata.org/ (accessed 12 October 2020).

Springer, A. E. and L. E. Stevens. 2009. Spheres of discharge. Hydrogeology Journal 17: 83–93. Available at: https://www.researchgate.net/publication/227165369_Spheres_of_discharge_of_springs (accessed 22 October 2020).

Springer, A., L. E. Stevens, and R. Harms. 2006. Inventory and classification of selected National Park Service springs on the Colorado Plateau. Southern Colorado Plateau Inventory & Monitoring Network. Fort Collins, Colorado. (not available to public online)

Stevens, L. E., J. Jenness, and J. D. Ledbetter. 2020. Springs and spring-dependent taxa of the Colorado River Basin, southwestern North America: geography, ecology and human impacts. Water 12: 1501. Available at: https://www.mdpi.com/2073-4441/12/5/1501 (accessed 5 January 2020).

Stevens, L. E., J. D. Ledbetter, A. E. Springer C. Campbell, L. Misztal, M. Joyce, and G. Hardwick. 2016. Arizona springs restoration handbook. Spring Stewardship Institute, Museum of Northern

Arizona, Flagstaff, Arizona and Sky Island Alliance, Tucson, Arizona. Available at: http://docs.springstewardship.org/PDF/SIA-Handbook_010916.pdf (accessed 22 October 2020).

Stortz, S. D., C. E. Aslan, T. D. Sisk, T. A. Chaudhry, J. M. Rundall, J. Palumbo, L. Zachmann, and B. Dickson. 2018. Natural resource condition assessment: Greater Grand Canyon landscape assessment. Natural Resource Report NPS/GRCA/NRR—2018/1645. National Park Service, Fort Collins, Colorado. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2253268 (accessed 7 October 2020).

Stuart, S. N., J. S. Chanson, N. A. Cox, B. E. Young, A. S. L. Rodrigues, D. L. Fischman, and R. W. Waller. 2004. Status and trends of amphibian declines and extinctions worldwide. Science 306: 1783–1786. Available at: https://science.sciencemag.org/content/sci/306/5702/1783.full.pdf?casa_token=FmN2KiYRHEMAAAAA:Yxj0PrLopAggjy1n0x1COG4CYuKv7VEa3K2WkUviJf9dhC62atHVxBq6rnUw_rtDGmqmTaerB5yXiA (accessed 28 July 2020).

Sullivan, T. J., G. T. McPherson, T. C. McDonnell, S. D. Mackey, and D. Moore. 2011a. Evaluation of the sensitivity of inventory and monitoring national parks to acidification effects from atmospheric sulfur and nitrogen deposition: Southern Colorado Plateau Network (SCPN). Natural Resource Report NPS/NRPC/ARD/NRR—2011/372. National Park Service, Denver, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2170600 (accessed 7 October 2020).

Sullivan, T. J., T. C. McDonnell, G. T. McPherson, S. D. Mackey, and D. Moore. 2011b. Evaluation of the sensitivity of inventory and monitoring national parks to nutrient enrichment effects from atmospheric nitrogen deposition: Southern Colorado Plateau Network (SCPN). Natural Resource Report NPS/NRPC/ARD/NRR2011/330. National Park Service, Denver, Colorado. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2168742 (accessed 7 October 2020).

Tanner, V. M. 1940. A biotic study of the Kaiparowits region of Utah. Great Basin Naturalist 1: 97–126. Available at: https://scholarsarchive.byu.edu/gbn/vol1/iss3/1/ (accessed 18 September 2020).

Tanner, V. M. 1958. Herpetology of Glen Canyon of the Upper Colorado River Basin. Herpetologica 14: 193–195. Available at: https://www.jstor.org/stable/3890482#metadata_info_tab_contents (accessed 4 March 2020).

Taylor, K. A. 2020. National Park Service air quality analysis methods: September 2020. Natural Resource Report NPS/NRSS/ARD/NRR—2017/1490. National Park Service, Fort Collins, Colorado. Available at: https://www.nps.gov/subjects/air/analysis-methods.htm (accessed 14 September 2020).

Taylor, H. E., K. Berghoff, E. D. Andrews, R. C. Antweiler, T. I Brinton, C. Miller, D. B. Peart, and D. Roth. 1997. Water quality of springs and seeps in Glen Canyon National Recreation Area. Available at: http://npshistory.com/publications/glca/nrtr-97-128.pdf (accessed 30 March 2020).

Taylor, H. E., J. R. Spence, R. C. Antweiler, K. Berghoff, T. I. Plowman, D. B. Peart, and D. A. Roth. 2004. Water quality and quantity of selected springs and seeps along the Colorado River Corridor, Utah and Arizona: Arches National Park, Canyonlands National Park, Glen Canyon National Recreation Area, and Grand Canyon National Park, 1997–98: U.S. Geological Survey Open-File Report 2003-496.

Tendick, A., J. Spence, M. Reed, K. Shulz, G. Kittel, K. Green, A. Wight, and G. Wakefield. 2017. Vegetation classification and mapping project report, Glen Canyon National Recreation Area and Rainbow Bridge National Monument. Natural Resource Report NPS/NCPN/NRR—2017/1500. National Park Service, Fort Collins, Colorado. Available at: https://www.nps.gov/im/vmi-glca-rabr.htm (accessed 11 November 2020).

Thomas L., M. Hendrie, C. Lauver, S. Monroe, N. Tancreto, S. Garman, and M. Miller. 2005. Vital Signs Monitoring Plan for the Southern Colorado Plateau Network: Phase III Report Appendices. Vital Signs Monitoring Plan for the Southern Colorado Plateau Network: Phase III Report Appendices. Flagstaff, AZ 86011. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2195921 (accessed 15 July 2020).

Thomas, L. P., M. N. Hendrie, C. L. Lauver, S. A. Monroe, N. J. Tancreto, S. L. Garman, M. E. Miller. 2006. Vital signs monitoring plan for the Southern Colorado Plateau Network. National Park Service. Flagstaff, AZ. Available at: https://irma.nps.gov/DataStore/DownloadFile/466432 (accessed 27 October 2020).

Thomas, R. 2020. Spatial modeling and validation survey of potential groundwater dependent ecosystems in the Escalante River watershed. Professional Masters of Science and Technology. University of Utah.

Thompson, R. S. and R. F. Fleming. 1996. Middle Pliocene vegetation: reconstructions, paleoclimatic inferences, and boundary conditions for climate modeling. Marine Micropaleontology 27: 27–49. (not available to online)

Tierney, J. E., C. J. Poulsen, I. P. Montañez, T. Bhattacharya, R. Feng, H. L. Ford, B. Hönisch, G. N. Inglis, S. V. Peterson, N. Sagoo, C. R. Tabor, K. Thirumalai, J. Zhu, N. J. Burls, G. L. Foster Y. Goddéris, B. T. Huber, L. C. Ivany, S. K. Turner, D. J. Lunt, J. C. McElwain, B. J. W. Mills, B. L. Otto-Bliesner, A. Ridgwell, and Y. G. Zhang. 2020. Past climates inform our future. Science 370: eaaay3701. Available at: https://science.sciencemag.org/content/370/6517/eaay3701 (accessed 9 December 2020).

U.S. Department of Agriculture (USDA). 2020a. Geospatial Data Gateway. Available at: https://gdg.sc.egov.usda.gov/GDGHome_DirectDownLoad.aspx (accessed 6 October 2020).

U.S. Department of Agriculture (USDA). 2020b. Wetland indicator status. Available at: https://plants.sc.egov.usda.gov/wetinfo.html#new_categories (accessed 22 October 2020).

U.S. Department of Agriculture (USDA), Natural Resource Conservation Service (NRCS). 2020. The PLANTS Database, Arizona state-listed noxious weeds. National Plant Data Team, Greensboro, NC 27401-4901 USA. Available at: http://plants.usda.gov (accessed 17 November 2020).

U.S. Environmental Protection Agency (USEPA). 2018. Analysis of the biological data collected from the Animas and San Juan rivers following the Gold King Mine release. U.S. Environmental Protection Agency, Washington, DC, EPA/830/R-18/003, November 2018. Available at: https://www.epa.gov/sites/production/files/2018-11/documents/gkm_bio_report_181129-508-final.pdf (accessed 8 February 2021).

U.S. Environmental Protection Agency (USEPA). 2020. What causes acid rain? Available at: https://www.epa.gov/acidrain/what-acid-rain (accessed 15 August 2020).

U.S. Fish and Wildlife Service (USFWS). 2011. Endangered and threatened wildlife and plants: 12-month finding on a petition to list the northern leopard frog in the western United States as threatened; Federal Register 76 (proposed rule 5 October 2011). Available at: https://www.govinfo.gov/content/pkg/FR-2011-10-05/pdf/2011-25498.pdf#page=2 (accessed 1 October 2020).

U.S. Fish and Wildlife Service (USFWS). 2018. Scientific review suggests reclassification of the razorback sucker from endangered to threatened. News Release. U.S. Fish and Wildlife Service. Available at: https://www.fws.gov/mountain-prairie/pressrel/2018/10042018-scientific-review-suggests-reclassification-of-the-razorback-sucker-from-endangered-to-threatened.php#.X_XiDthKiUl (accessed 6 January 2020).

U.S. Geological Survey (USGS). 2016. The StreamStats program. Available at: http://streamstats.usgs.gov (accessed 11 January 2021).

U.S. Geological Survey (USGS). 2018. Gap Analysis Program (GAP). Protected Areas Database of the United States (PAD-US): U. S. Geological Survey data release. Available at: http://doi.org/10.5066/P955KPLE. (accessed 24 March 2021).

U.S. Geological Survey (USGS). 2020a. Assessing impacts to ecosystems from uranium mining in the Grand Canyon region. Available at: https://www.usgs.gov/centers/fort/science/assessing-impacts-ecosystems-uranium-mining-grand-canyon-region?qt-science_center_objects=0#qt-science_center_objects (accessed 22 July 2020).

U.S. Geological Survey (USGS). 2020b. USGS National Hydrography Dataset (NHD). Model version 2.2.1. U.S. Geological Survey, Reston, Virginia. Available at: https://www.sciencebase.gov/catalog/item/5136012ce4b03b8ec4025bf7 (accessed 3 August 2020).

U.S. Geological Survey (USGS). 2020c. National Water Information System. Available at: https://waterdata.usgs.gov/nwis (accessed 22 October 2020).

U.S. Geological Survey (USGS). 2020d. Amphibian Research and Monitoring Initiative trends database. Available at: https://armi.usgs.gov/projects/terms.php?continue=%2Fprojects%2Festimates_datasets.php (accessed 18 September 2020).

Utah Department of Agriculture and Food. 2019. State of Utah noxious weed list. Available at: https://ag.utah.gov/farmers/plants-industry/noxious-weed-control-resources/state-of-utah-noxious-weed-list/ (accessed 17 November 2020).

Utah Department of Environmental Quality (UDEQ). 2018. Water quality. Utah's draft 2018/2020 303(d) assessment methods. Salt Lake City, Utah. Utah Department of Environmental Quality. Available at: https://documents.deq.utah.gov/water-quality/monitoring-reporting/integrated-report/DWQ-2018-012546.pdf (accessed 27 October 2020).

Utah Division of Water Quality (UDWQ). 2017. Utah's final 2016 integrated report. Salt Lake City, Utah. Utah Department of Environmental Quality. Available at: https://documents.deq.utah.gov/water-quality/monitoring-reporting/integrated-report/DWQ-2017-004941.pdf (accessed 17 November 2020).

Utah Division of Water Quality (UDWQ). 2020. Utah's draft combined 2018/2020 integrated report. Salt Lake City, Utah. Utah Department of Environmental Quality. Available at: https://documents.deq.utah.gov/water-quality/monitoring-reporting/integrated-report/DWQ-2020-021402.pdf (accessed 17 November 2020).

Utah Division of Wildlife Resources (UDWR). 2006. Conservation and management plan for three fish species in Utah: addressing the needs for roundtail chub (*Gila robusta*), bluehead sucker (*Catostomus discobolus*), and flannelmouth sucker (*Catostomus latipinnis*). Utah Department of Natural Resources, Salt Lake City, Utah. Available at: https://cpw.state.co.us/Documents/WildlifeSpecies/SpeciesOfConcern/RecoveryPlans/ChubSuckerRangewideConservationAgreementandStrategy01-04-07.pdf (accessed 9 July 2020).

Utah Division of Wildlife Resources (UDWR). 2008. Escalante River native fish surveys between Boulder Creek and Harris Wash. Investigator's annual report to the National Park Service. Available at: https://irma.nps.gov/RPRS/IAR/Profile/47105 (accessed 22 December 2020).

Utah Division of Wildlife Resources (UDWR). 2009. Three species: roundtail chub (*Gila robusta*), bluehead sucker (*Catostomus discobolus*), and flannelmouth sucker (*Catostomus latipinnis*) monitoring summary, statewide 2009. Utah Department of Natural Resources, Salt Lake City, Utah. Available at: https://digitallibrary.utah.gov/awweb/awarchive?type=file&item=35409 (accessed 17 December 2020).

Utah Wildlife Action Plan (WAP) Joint Team. 2015. Utah Wildlife Action Plan: A plan for managing native wildlife species and their habitats to help prevent listing under the Endangered Species Act. Publication number 15-14. Utah Division of Wildlife Resources, Salt Lake City,

Utah, USA. Available at: https://wildlife.utah.gov/discover/wildlife-action-plan.html (accessed 5 October 2020).

Walters, C. J., B. T. van Poorten, and L. G. Coggins. 2012. Bioenergetics and population dynamics of flannelmouth sucker and bluehead sucker in Grand Canyon as evidenced by tag recapture observations. Transactions of the American Fisheries Society 141: 158–173.

Weiss, S. J., F. O. Otis, and O. E. Maughan. 1998. Spawning ecology of flannelmouth sucker, *Catostomus latipinnis* (Catostomidae), in two small tributaries of the lower Colorado River. Environmental Biology of Fishes 52: 419–433. Available at: https://link.springer.com/article/10.1023/A:1007497513762 (accessed 6 January 2021).

Weissinger, R. H., B. R. Blackwell, K. Keteles, W. A. Battaglin, and P. M. Bradley. 2018. Bioactive contaminants of emerging concern in national park waters of the northern Colorado Plateau, USA. Science of the Total Environment 636: 910–918. Available at: https://www.sciencedirect.com/science/article/pii/S0048969718315109?via%3Dihub (accessed 18 September 2020).

Weissinger, R. H., D. W. Perkins, and E. C. Dinger. 2012. Biodiversity, water chemistry, physical characteristics, and anthropogenic disturbance gradients of sandstone springs on the Colorado Plateau. Western North American Naturalist 72: 393–406. Available at: https://scholarsarchive.byu.edu/cgi/viewcontent.cgi?article=1586&context=wnan (accessed 28 July 2020).

Weissinger, R, T. E. Philippi, and D. Thoma. 2016. Linking climate to changing discharge at springs in Arches National Park, Utah, USA. Ecosphere 7: 1–12. Available at: https://esajournals.onlinelibrary.wiley.com/doi/full/10.1002/ecs2.1491 (accessed 21 October 2020).

White P. S. and S. T. A. Pickett. 1985. Natural disturbance and patch dynamics: An introduction. Pages 3–13 in S. T. A. Pickett and P. W. White, editors. The ecology of natural disturbance and patch dynamics. Academic Press, New York.

Wild and Free Roaming Horse and Burros Act. 1971. Public Law 92-195. Available at: https://uslaw.link/citation/us-law/public/92/195 (accessed 25 March 2021).

Wilkowske, C. D., T. A. Kenney, and S. J. Wright. 2011. Methods for estimating monthly and annual streamflow statistics at ungagged sites in Utah. U.S. Geological Survey Scientific Investigations Report 2008-5230. Available at: https://pubs.usgs.gov/sir/2008/5230/ (accessed 24 November 2020).

Williamson, R. 1985. A baseline chemical analysis of selected springs in Glen Canyon National Recreation Area. National Park Service. Available at: https://irma.nps.gov/DataStore/Reference/Profile/13592 (accessed 27 October 2020).

Wood, C. W. and D. B. Kimball. 1987. Water resources management plan and environmental assessment. Glen Canyon National Recreation Area. Available at: https://archive.org/details/waterresourcesma00utah (accessed 9 November 2020).

Woodhouse, E. T. and R. A. Fridell. 2017. Three species population monitoring in the southern region. Utah Division of Wildlife Resources, Southern Region.

Woodward, B. D., P. H. Evangelista, N. E. Young, A. G. Vorster, A. M. West, S. L. Carroll, R. K. Girma, E. Z. Hatcher, R. Anderson, M. L. Vahsen, A. Vashist, T. Mayer, D. Carver, and C. Jarnevich. 2018. CO-RIP: A riparian vegetation and corridor extent dataset for Colorado River Basin Streams and Rivers. International Journal of Geo-Information 7: 397. Available at: https://www.mdpi.com/2220-9964/7/10/397 (accessed 3 December 2020).

Xu, Weixin, D. Yang, Y. Li, and R. Xiao. 2016. Correlation of Mackenzie River discharge and NDVI relationship. Canadian Journal of Remote Sensing 42: 292–306. Available at: https://www.researchgate.net/publication/299652463_Correlation_Analysis_of_Mackenzie_River_Discharge_and_NDVI_Relationship (accessed 29 March 2021).

Zeigler, M. P. and M. E. Ruhl. 2016. Small-bodied fishes monitoring in the San Juan River: 2015. Annual Report. San Juan River Basin Recovery Implementation Program. New Mexico Department of Game and Fish, Santa Fe, New Mexico. Available at: https://www.fws.gov/southwest/sjrip/pdf/DOC_Small-bodied_Fishes_Monitoring_SJR_2015.pdf (accessed 22 December 2020).

Zeigler, M. P. and J. M. Wick. 2019. Small-bodied fishes monitoring in the San Juan River: 2018. Annual final report submitted to Bureau of Reclamation. New Mexico Department of Game and Fish. Available at: https://www.fws.gov/southwest/sjrip/pdf/Small-bodied%20fishes%20monitoring%20on%20the%20San%20Juan%20River%20-%202018.pdf (accessed 22 December 2020).

Zylstra E. R., R. J. Steidl, D. E. Swann, and K. Ratzlaff. 2015. Hydrologic variability governs population dynamics of a vulnerable amphibian in an arid environment. PLoS ONE 10: e0125670. Available at: https://doi.org/10.1371/journal.pone.0125670 (accessed 18 September 2020).

Appendix A. GLCA Manager Questions and Information Needs

The questions and information needs listed in Table A-1 were posed by GLCA managers during the NRCA study scoping process. When possible, during the NRCA data gathering, analysis, and technical report development phases, information to address these questions and needs were presented in Chapters 2–4. Table A-1 also includes abbreviated responses to the questions/needs and the chapters and sections where a reader can locate more in-depth information pertaining to each. If a question/need remained unaddressed, suggestions for informing the knowledge gap were presented in the appropriate Chapter 4 resource summary to inform potential management actions in the future.

Table A-1. GLCA natural resource manager question, need, abbreviated answer, and NRCA report chapter/section for further information summary.

Manager Question or Needs	Abbreviated Answer(s)	Chapter/Section for Additional Information
With changing climate, which species are likely to survive in the park? Specifically, which endemic or unique plant, wildlife, and insect species could be lost in the near future?	For tinajas, the limited inventories did not include any endemics or unique species and remains a knowledge gap. For springs and seeps, those supplied by groundwater with long residence times, located in deeply shaded, north-facing alcoves, and/or ones that support relict species are more likely to serve as climate refuges for unique and endemic species. But species with low dispersal abilities or sensitivity to water loss and temperature extremes may be the first to be lost from springs.	• Non-native Invasive Plants: 2.1.3 • Climate Change: 2.1.7 • Tinajas: 3.1.2, 3.1.3 • Springs & Seeps: 3.3.6 • Tinajas Summary: 4.3.1
What actions to further study, monitor, and protect these species (mentioned above) should be taken?	In addition to water quality and quantity, plants, and disturbance, biological surveys of vertebrates and invertebrates should also be included in future monitoring efforts of tinajas. For springs and seeps, the authors recommend using the NCPN monitoring strategy with a few additional measures. Management actions at springs could include fencing to exclude ungulates, controlling invasive species, and installing mechanisms that help pool water. Additional actions may include completing the location analysis and prioritizing the locations for management.	• Tinajas: 3.1.3 • Tinajas Summary: 4.3.1 • Springs & Seeps: 3.3.6
Where does water collect, forming tinajas?	Tinajas on the Colorado Plateau tend to occur in incipient ephemeral channels in sandstone formations. Analysis suggests an area of 806 km^2 (311 mi^2) for potential tinaja occurrence in GLCA.	• Tinajas: 3.1.1, 3.1.2, 3.1.3 • Tinajas Summary: 4.3.1
How are other parks managing tinajas?	Authors did not discover parks managing tinajas, only monitoring them. Potential management activities are summarized in Chapter 4.	• Tinajas: 3.1.3 • Tinajas Summary: 4.3.1

Table A-1 (continue). GLCA natural resource manager question, need, abbreviated answer, and NRCA report chapter/section for further information summary.

Manager Question or Needs	Abbreviated Answer(s)	Chapter/Section for Additional Information
When does mineral extraction become a pressing resource issue to springs and seeps?	Authors recommend monitoring for toxic parameters due to surrounding mineral extraction activities.	• Resource Extraction: 2.1.6 • Water Quality: 3.2.1, 3.2.3
Are there any threats from airborne or atmospheric contaminants, such as heavy metals or nitrogen fertilization that should be monitored, which could impact the quality of GLCA's water sources of interest?	With many of the coal-fired plants closing throughout the region, this may reduce the amount of airborne pollutants. Springs & seeps may transport pollutants to surface waters. Threats from heavy metals or nitrogen fertilizers warrant continued and perhaps more intensive monitoring of water quality, especially at amphibian breeding pools. During 2012 to 2016, at least one contaminant of emerging concern was found in water or sediments in GLCA. These pollutants can then accumulate in amphibians, fishes, and their prey, which could contribute to population declines.	• Air Quality: 2.1.5 • Water Quality: 3.2.1, 3.2.3 • Amphibians: 3.5.3 • N. Leopard Frog: 3.6.4 • Amphibians & • N. Leopard Frog Summary: 4.3.4 • Fishes: 3.7.4 • Fishes Summary: 4.3.5
Should adjustments to livestock grazing animal unit months, or periods of use be considered?	There were no differences in core water quality measures (other than specific conductance) for springs accessible versus inaccessible to non-native grazers, but more study is needed to confirm this finding. Of 29 springs evaluated for impacts, 24% were functioning-at-risk and 7% were degraded due to livestock, drought, non-native plants, and spring development for livestock watering. This suggests that some management action may be necessary to protect and restore degraded springs.	• Ranching & Livestock Management: 2.1.4 • Water Quality: 3.2.2, 3.2.3 • Springs & Seeps: 3.3.4 • Springs & Seeps, including water quality Summary: 4.3.2
Should improvements or upgrades to water developments (excluding water catchments) be considered to better protect springs and seeps? What, if any, management actions should occur to protect springs and seeps?	More frequent livestock water tank maintenance will increase the amount of water easily accessed by livestock and native ungulates, which may reduce the use of natural springs. Functioning-at-risk springs may be of higher priority to prevent further degradation. Degraded springs could be prioritized for restoration. Fencing, non-native invasive species control, and installing mechanisms to pool and direct water would better protect springs and seeps	• Water Quality: 3.2.2, 3.2.3 • Springs & Seeps: 3.3.4 • Springs & Seeps, including water quality Summary: 4.3.2

Table A-1 (continue). GLCA natural resource manager question, need, abbreviated answer, and NRCA report chapter/section for further information summary.

Manager Question or Needs	Abbreviated Answer(s)	Chapter/Section for Additional Information
Do increased erosion, downcutting of channels, or deposition threaten springs and seeps?	Of the springs that are accessible to livestock (and perhaps visitors), downcutting of channels, soil deposition, and nitrogen enhancement are potential threats to spring ecosystems and should continue to be monitored. Of 29 springs evaluated, 24% were functioning-at-risk and 7% were degraded due to livestock, including developments for watering, drought, and non-native plants. In addition, seepage through the permeable sandstone formations results in erosion and mass wasting of rock walls (Graham 2016). While erosion is a natural physical process that is responsible for creating hanging gardens, falling rocks that crush vegetation are common in some hanging gardens (Stevens et al. 2016) and should also continue to be monitored.	• Water Quality: 3.2.3 • Springs & Seeps: 3.3.4 • Springs & Seeps, including water quality Summary: 4.3.2
What type of elevational shift or desertification will occur with warming temperatures and altered precipitation cycles?	Endemic plants found at springs in GLCA generally occur within a narrow elevation band from 1,000–2,000 m (3,281–6,562 ft) above sea level. Above 2,000 m (6,562 ft), hanging gardens and associated geology become rare. Based on the distribution of springs in GLCA and predicted elevational shifts in temperature, Spence and Cushing (2019) estimate that 77% of springs and 80% of hanging gardens will experience temperatures above the threshold of endemic plant species by 2100 under an intermediate climate scenario. However, variability in microclimate across springs may ameliorate climate change effects. For rivers and streams, a warmer and drier climate may result in “terrestrialization” of the riparian zone, or conversion to plants that sometimes use groundwater for survival or upland plants. While moderate water depletions may alter existing riparian plant composition and structure, severe water depletions will result in desertification.	• Climate Change: 2.1.7 • Non-native Invasive Plants: 2.1.3 • Springs & Seeps: 3.3.4 Riparian Zone: 3.4.4
What, if any, actions can and should be taken to protect the hanging gardens and their associated plant/wildlife/insect assemblages should the aquifers supporting them begin to dry up?	Prioritizing the springs and seeps for groundwater studies, capturing water, assisting endemic migration, controlling non-native invasive species, and informing backcountry users of the importance of this resource, along with partnering with others, will help protect this resource. These are complex environments that require an interdisciplinary and multi-partnership management approach for long-term conservation.	• Springs & Seeps: 3.3.4 • Springs & Seeps, including water quality Summary: 4.3.2

Table A-1 (continue). GLCA natural resource manager question, need, abbreviated answer, and NRCA report chapter/section for further information summary.

Manager Question or Needs	Abbreviated Answer(s)	Chapter/Section for Additional Information
How will a decreasing water supply impact spring-dependent species? When discharge rates drop, how much are springs affected?	Thresholds for change in spring ecosystems in GLCA and on the Colorado Plateau are unknown (Perkins et al. 2018). Other studies have shown that even small declines in discharge have large effects on spring-fed aquatic environments. This is a data gap and groundwater studies would help inform this aspect of springs but limited (and older) discharge data were summarized and presented in section 3.2.2.	• Water Quality: 3.2.2 • Springs & Seeps: 3.3.4 • Springs & Seeps, including water quality Summary: 4.3.2
How do endemics compare/contrast within each watershed of interest?	Observers reported 144 native species in springs surveyed from 1992 to 2018. Refer to Figure 3.3.4-2, which shows the mean plant species richness, including total native, native wetland, endemic, and relict species, by watershed.	• Springs & Seeps: 3.3.4
How will invasive grasses respond to increased nitrogen deposition throughout the park?	Increases in nitrogen deposition, coupled with grazing impacts to soils and vegetation, promote invasions of fast growing nonnative annual grasses (e.g., cheatgrass) and forbs (e.g., Russian thistle) at the expense of native species (Brooks 2003; Schwinning et al. 2005; Allen et al. 2009). Russian olive, a nitrogen-fixing tree, may increase soil nitrogen by 55% (DeCant 2008). However, Katz et al. 2020 found that the additional nitrogen did not facilitate the colonization of invasive species in riparian areas.	• Air Quality: 2.1.5 • Riparian Zone: 3.4.4 • Riparian Zone Summary: 4.3.3
Which non-native invasive plants are currently in Sonoran and/or Mojave Deserts, and could those become the new invasive plants in GLCA side canyon streams/riparian areas?	Predicting which species are likely to invade riparian areas in the coming decades is complicated by the fact that there is no current climate regime similar to future predicted climate for GLCA. However, Gremer et al. (2018) suggest that future climate conditions in GLCA may lead to greater dominance of shrubs relative to grasses. In recent years, the non-native desert willow (*Chilopsis linearis*), native to the Sonoran and Mojave Deserts, has appeared in some areas around Lake Powell and some side canyons. This species is likely to spread further along intermittent streams. This is a data gap.	• Non-native Invasive Plants: 2.1.3 • Riparian Zone: 3.4.4 • Riparian Zone Summary: 4.3.3

Table A-1 (continue). GLCA natural resource manager question, need, abbreviated answer, and NRCA report chapter/section for further information summary.

Manager Question or Needs	Abbreviated Answer(s)	Chapter/Section for Additional Information
Do threats from the loss of water sources for amphibians warrant additional monitoring and management actions?	Amphibians face a number of threats, including water loss due to changing climate and plants overtaking breeding pools (e.g., *Phragmites*). The loss of water sources alone probably warrants additional monitoring and management of amphibians, irrespective of the many other threats to this resource. Identifying areas of high connectivity for restoration and guiding visitor use, developing an ORV plan, limiting livestock access, and removing non-native invasive plant and animal species are potential actions. Conducting these activities with partners will augment the monitoring and management actions.	• Amphibians: 3.5.3 • N. Leopard Frog: 3.6.4 Amphibians & • N. Leopard Frog Summary: 4.3.4
Do threats from the loss of water sources for fish warrant additional monitoring and management actions?	Yes, especially in areas characterized by shorter stretches of perennial streams with ample water flow and increasing temperature or in areas of significant water diversions. Changes in hydrology, natural or otherwise, also influence the amount of available habitat, sedimentation, and the formation of barriers to fish travel (e.g., waterfalls).	• Fishes: 3.7.4 • Fishes Summary: 4.3.5
How will the small native fishes respond to Russian olive control/ removal along the Escalante River as it is restored to a pool-riffle habitat?	The cascading effect of Russian olive removal is not well studied and remains a topic of needed research. This is a data gap.	• Fishes: 3.7.4 • Fishes Summary: 4.3.5
How much fish habitat remains in the park?	The authors could not answer this question for the entire park with the available data, but good quality habitat is present in the upper reach of the Escalante River and in portions of the San Juan River.	• Fishes: 3.7.4 • Fishes Summary: 4.3.5

Appendix B. Condition Rating Statements

The five-level condition rating statements for the springs & seeps, riparian zone, northern leopard frog, and fishes condition assessments are presented in Tables B-1 to B-4, respectively.

Table B-1. Condition rating statements for the status of springs & seeps indicators.

Condition Rating	Native Vegetation	Impacts
Good	Native plants, particularly endemic and relict species, are widespread across spring types and watersheds.	The majority (<80%) of springs are rated as Intact – functioning spring, mostly natural background disturbances occurring. The remaining springs are rated as Functioning-at-Risk (altered disturbance regimes present, and some wetland declines), and <5% of springs are rated as non-functional (severely degraded, most functions and biotic elements lost).
Good/Fair	–	–
Fair	Most species are widespread, but some endemic and/or relict species appear isolated in their distribution (e.g., restricted to a single watershed or occurring at only a small number of springs).	Up to 50% of springs are rated as Functioning-at-Risk and <5% of springs are rated as non-functional (severely degraded, most functions and biotic elements lost). The remaining springs are rated as Intact.
Fair/Poor	–	–
Poor	A high degree of isolation for many native species, especially those considered endemic or relict species.	More than 50% of springs are rated as Non-Functional with the remaining springs either Intact or Functioning-at-Risk.

Table B-2. Condition rating statements for the status of riparian zone indicators.

Condition Rating	Water Quantity and Availability	Stream Health	Vegetation
Good	Flow variability mimics historic patterns and riparian plant extent occurs along most stream reaches.	No stream impairments identified, and aquatic intactness is characterized as moderately high, high, or very high.	Non-native plants, particularly the most problematic species, occur in limited areas, and there is only minor (10–33%) or negligible (<10%) departure from natural historic conditions across a majority area of the streams evaluated.
Good/Fair	–	–	–

Table B-2 (continued). Condition rating statements for the status of riparian zone indicators.

Condition Rating	Water Quantity and Availability	Stream Health	Vegetation
Fair	There is moderate departure from flow variability and riparian plant extent may be absent from some stream reaches and/or riparian plants appear decadent along some stream reaches where they were previously vigorous.	Either stream impairments are identified for some but not all reaches of surveyed rivers or aquatic intactness is characterized by moderately low, low or very low.	Non-native species, some of which may be problematic, occur in dense stands in some areas but are not considered widespread, or species not considered problematic are widespread. Furthermore, vegetation departure may be significant (33–66%) in a majority of riparian areas evaluated while other areas exhibit minor or negligible departure. Few to no areas exhibit large departure (>66%).
Fair/Poor	–	–	–
Poor	Flow variability is severely degraded and departed from historic conditions and riparian plants are absent or decadent along a substantial portion of stream reaches.	Stream impairments are widespread and aquatic intactness is characterized as low or very low.	Vegetation departure from historic conditions is large (>66%) over most of the riparian areas of interest. Non-native plants, some of which are problematic, are widespread and dominate certain areas.

Table B-3. Condition rating statements for the status of northern leopard frog indicators.

Condition Rating	Occupancy	Reproduction	Disease	Plant Encroachment
Good	Leopard frogs are observed at all or nearly all locations surveyed in all or nearly all years visited.	Breeding evidence observed in all or most occupied areas in all or nearly all years visited.	No non-native/introduced diseases detected, and any native diseases are rare.	Phragmites has not invaded known occupied habitats nor is it widespread in other areas that are potentially inhabited by northern leopard frogs.
Good/Fair	–	–	–	–
Fair	Leopard frogs are documented in historically occupied sites in most years.	Breeding evidence observed in most sites and years, but some sites lack evidence of breeding.	Non-native and/or native disease(s) detected at a few sites or persistently at one or two sites.	Phragmites occurs in some occupied habitats but does not appear widespread.

Table B-3 (continued). Condition rating statements for the status of northern leopard frog indicators.

Condition Rating	Occupancy	Reproduction	Disease	Plant Encroachment
Fair/Poor	–	–	–	–
Poor	Leopard frogs are absent in previously known occupied areas.	No or little evidence of breeding in all or nearly all sites visited in most years.	Non-native/introduced diseases are widespread and persistent over time. Native diseases may also be widespread and persistent.	Phragmites is widespread in occupied habitats and other areas that may be occupied.

Table B-4. Condition rating statements for the status of fishes indicators.

Condition Rating	Water Quantity and Availability	Water Quality	Biological Community	Habitat Quality and Availability
Good	Flow variability mimics historic patterns, particularly during spring.	All water quality measures meet aquatic life requirements for warm water species.	All four native species are present with recruitment into the adult population. Non-native species are absent, or if present, are not species known to disrupt native species.	Habitats along a majority of stream reaches are in pristine conditions with suitable benthic and hydraulic diversity to support the needs of native fish species.
Good/Fair	–	One or more water quality measures suggest the potential for impacts to warm water fishes, but impacts have not been reported.	–	Habitat quality features are slightly altered or reduced but still considered suitable for native fish species.
Fair	There is moderate departure from flow variability, but spring flows remain near historic conditions.	While basic water quality measures support aquatic life of warm water species, water quality problems have caused measurable impacts. However, effects are localized and not widespread or persistent.	Both non-native and native species are present, but recruitment of native species remains high.	Measurable but not severe degradation in benthic substrate composition and/or hydraulic features. Most required features are present, especially those required for reproduction.

Table B-4. Condition rating statements for the status of fishes indicators.

Condition Rating	Water Quantity and Availability	Water Quality	Biological Community	Habitat Quality and Availability
Fair/Poor	–	Water quality problems have caused severe impacts that are either widespread or persistent.	–	Selected habitat loss or alteration has caused severe degradation in some, but not all aspects of benthic substrate diversity and hydraulic features.
Poor	Flow variability is severely degraded and departed from historic conditions.	Measures of water quality are not consistent with supporting aquatic life of warm water species. Impacts are severe, persistent, and widespread.	Native species are absent or severely reduced in numbers and the community is dominated by non-native species.	Habitats along a majority of stream reaches severely degraded with unsuitable benthic and hydraulic diversity that does not support the needs of native fish species.

Appendix C. Drivers and Stressors Diagram & Tabular View

Figure C-1 shows the drivers and stressors conceptual model by focal resource, including interrelationships between the stressors. Table C-1 shows the drivers and stressors conceptual model in tabular format.

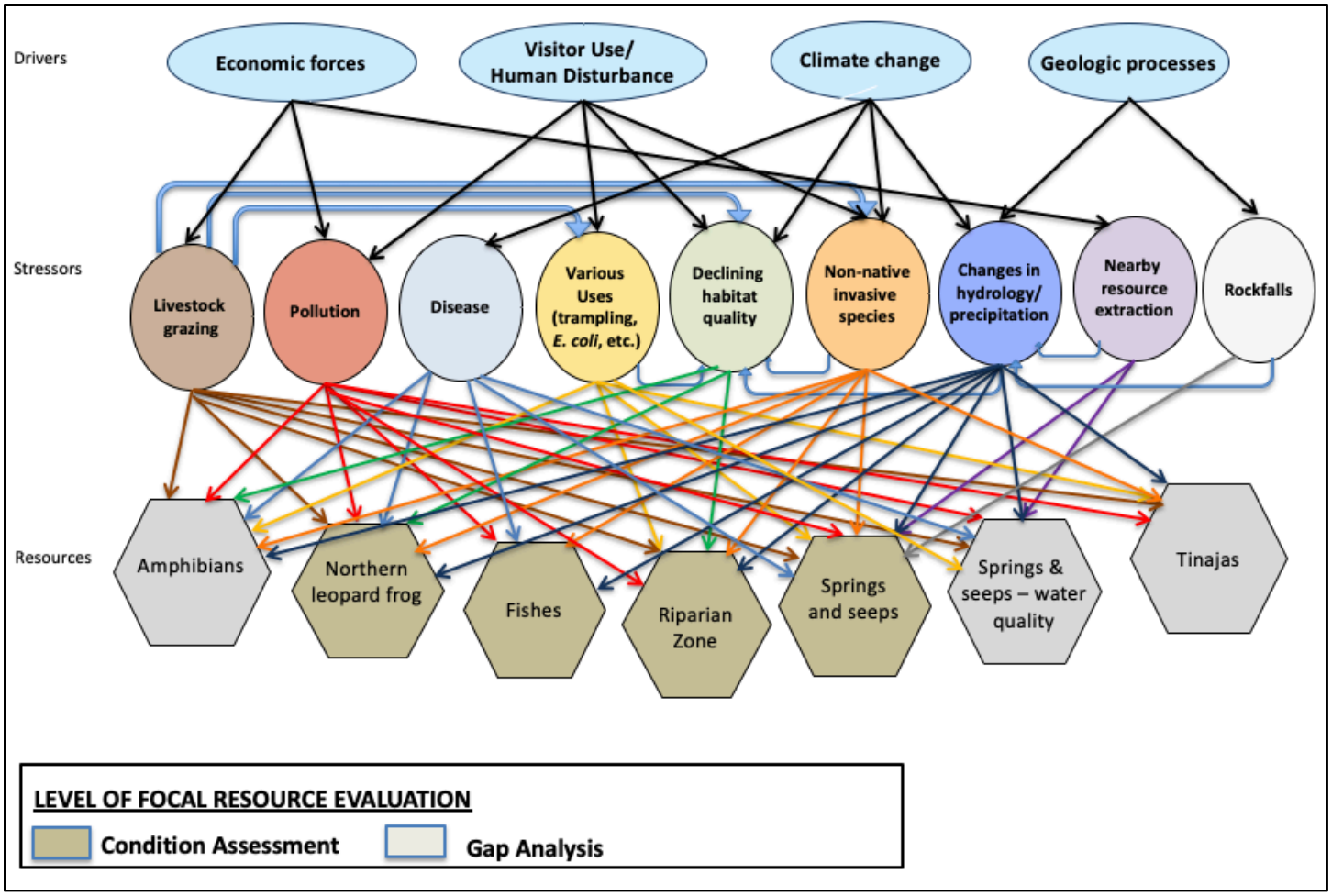


Figure C-1. The drivers and stressors conceptual model used to depict and discuss influences of resource conditions. Figure Credit: Mark Brunson.

Table C-1. The drivers and stressors conceptual model shown in Figure C-1, depicted in tabular format.

Focal Resources	Driver or Stressor Emphasis								
	Climate Change	**Upland Activities** [1]	**Pollution**	**Livestock Use**	**Non-native Invasive Species**	**Disease**	**Visitor Use**	**Resource Extraction**	**Other**
Tinajas	X	–	X	X	X	–	X	–	–
Water Quality (springs)	X	X	X	X	–	X	X	X	–
Springs & Seeps	X	X	X	X	X	X	X	X	X [2]
Riparian Zone	X	X	X	X	X	–	X	–	–
Amphibians	X	X	X	X	X	X	X	–	X [3]
Northern Leopard Frog	X	X	X	X	X	X	X	–	X [3]
Fishes	X	X	X	–	X	X	X	–	X [4]

[1] Includes declining habitat quality and changes in hydrology drivers/stressors in Figure C-1.

[2] Geohazards (rockfall).

[3] Lack of habitat connectivity; genetic isolation; dust and noise pollution from ORV use.

[4] Uncertain about nematode nativity.

Appendix D. Manager-Scientist Responses by Resource and Driver or Stressor

Tables D-1 through D-7 present the GLCA manager actions by focal resource and associated drivers or stressors.

Table D-1. Responses for tinajas.

	Primary Driver or Stressor Emphasis				
Action Category	**Climate Change**	**Livestock Use**	**Non-natives**	**Visitor Use**	**Other**
Field-based Management	–	Limited opportunities for fencing	Control work	–	–
Research, Monitoring, & Inventory	Changes in endemic species, water quality	–	Non-native species inventory	–	Wildlife use monitoring
Education & Interpretation	–	–	–	Importance of tinajas (e.g., wildlife), effects of sunscreen or fecal contamination	–
Partnerships	–	–	–	–	Capitol Reef and Canyonlands NPs and BLM
Zoning & Planning	–	–	–	Backcountry management plans	–
Law Enforcement	–	–	–	–	–
Laws, Policies & Guidelines	–	–	–	–	–

Table D-2. Responses for water quality of springs & seeps.

Action Category	Primary Driver or Stressor Emphasis						
	Climate Change	**Upland Activities**	**Pollution**	**Livestock Use**	**Visitor Use**	**Resource Extraction**	**Other**
Field-based Management	–	Sediment loading mitigation	–	Fencing	Restrict camping locations	–	–
Research, Monitoring, & Inventory	Changes in hydrology	Changes in hydrology	Effects on water quality (incl. Hg)	*E. coli* monitoring (citizen science)	*E. coli* monitoring (citizen science)	Fracking or uranium	Cyanobacteria, *Didymosphenia geminata* (rock snot)
Education & Interpretation	–	–	–	–	How to protect water quality when camping	–	–
Partnerships	–	BLM	–	BLM, Navajo Nation, citizen science	–	BLM	–
Zoning & Planning	–	–	–	–	Backcountry plans	–	–
Law Enforcement	–	–	–	BLM law enforcement on feral livestock	Fence issues	BLM law enforcement on neighboring mineral extraction	–
Laws, Policies & Guidelines	–	–	Clean Water Act	–	–	Mitigation requirement	–

Table D-3. Responses for springs & seeps.

Action Category	Primary Driver or Stressor Emphasis						
	Climate Change	**Upland Activities**	**Livestock Use**	**Non-natives**	**Visitor Use**	**Resource Extraction**	**Other**
Field-based Management	Capture and direct water, Assisted migration	–	Fencing	Control activities	–	–	Control of “water-hogging” species
Research, Monitoring, & Inventory	Aquifer alterations, document endemics, refugia	Changes in hydrology	–	Monitor non-natives	Backcountry water use, *E. coli*	Tar sands effect on aquifers	Monitor rockfall, Species distribution modeling, rock snot
Education & Interpretation	Climate change impacts to seeps/springs	–	–	–	Education on hanging gardens, desert springs/seeps	–	–
Partnerships	–	–	–	–	–	–	Grand Canyon Trust, ERWP
Zoning & Planning	–	–	–	–	Backcountry management plans	–	–
Law Enforcement	–	–	–	–	Fire restriction	–	–
Laws, Policies & Guidelines	–	–	–	Restrict development near springs	–	–	–

Table D-4. Responses for riparian zone.

Action Category	Primary Driver or Stressor Emphasis					
	Climate Change	**Upland Activities**	**Livestock Use**	**Non-natives**	**Visitor Use**	**Declining Habitat Quality**
Field-based Management	–	–	Exclosures and fencing, general livestock management	Control of non-natives	Restrictions on visitor numbers	Restoration (removal & planting), beaver dam analogs
Research, Monitoring, & Inventory	Changes in hydrology, increase in plant disease susceptibility	Changes in water withdrawals	–	Which NNIS will replace tamarisk? Exotic insects	–	Monitor beavers
Education & Interpretation	–	–	–	Invasive riparian species education	Education on values of riparian areas	–
Partnerships	–	–	Grand Staircase-Escalante (GSENM) NM, Escalante River Watershed Partners (ERWP), BLM, Sierra Club/Wilderness Volunteers	GSENM, ERWP, BLM, Sierra Club/Wilderness Volunteers	GSENM, ERWP, BLM, Sierra Club/Wilderness Volunteers	BLM
Zoning & Planning	–	–	–	–	Backcountry management plan (visitor use)	–
Law Enforcement	–	–	–	–	Fire restriction	–
Laws, Policies & Guidelines	–	Upstream efforts to leave more water in Colorado River	–	–	–	–

Table D-5. Responses for amphibians.

Action Category	Primary Driver or Stressor Emphasis							
	Climate Change	**Upland Activities**	**Pollution**	**Livestock Use**	**Non-natives**	**Disease**	**Visitor Use**	**Other**
Field-based Management	Assisted migration	–	–	Exclosures	Remove high priority invasive plants, bullfrogs, & crayfish	–	Restoration of heavily disturbed areas	Declining habitat quality
Research, Monitoring, & Inventory	Hydrologic alterations, changes in temperature, phenology; tinaja monitoring for toads & tree frogs	–	Utilize NPS Air Resources Division monitoring data, citizen science (dragonflies)	Upland long-term plant and biological soil crusts (BSC) monitoring	Ravenna grass effects on wetlands	Chytrid monitoring	Identify if known locations are adjacent to ORV trails; Research on visitor impacts	Identify areas of potential connectivity for future restoration; additional inventories
Education & Interpretation	General education on climate change effects	–	Education on effects of personal care chemicals	–	–	Effects of trampling & spreading Chytrid-handout for backcountry users, signage	Effects of trampling & spreading Chytrid-handout for backcountry users, signage	–
Partnerships	Direct work w/fish & game agencies	Hydrologic alterations	Work with Utah DWQ	BLM allotment managers	Grand Canyon Wildlands Council	–	–	–
Zoning & Planning	–	–	–	–	–	–	Visitor use limits	Spatial limits on visitor use
Law Enforcement	–	–	–	–	–	–	–	–
Laws, Policies & Guidelines	NPS-wide policy directives	–	Improved conditions due to coal-fired plant closures	–	–	–	Continued increase in visitation	Threatened or endangered species listing

Table D-6. Responses for northern leopard frog.

Action Category	Primary Driver or Stressor Emphasis							
	Climate Change	**Upland Activities**	**Pollution**	**Livestock Use**	**Non-natives**	**Disease**	**Visitor Use**	**Other**
Field-based Management	Assisted migration	–	–	Exclosures	Remove high priority invasive plants, bullfrogs, & crayfish	–	Restoration of heavily disturbed areas	Reintroduction
Research, Monitoring, & Inventory	Hydrologic alterations, changes in temperature, phenology	–	Utilize NPS Air Resources Division monitoring data, citizen science (dragonflies)	Upland long-term plant and BSC monitoring	Ravenna grass effects on wetlands	Chytrid monitoring	Identify if known locations are adjacent to ORV trails; research on visitor impacts	Identify areas of connectivity potential for future restoration
Education & Interpretation	General education on climate change effects	–	Education on effects of personal care chemicals	–	–	Effects of trampling & spreading Chytrid-handout for backcountry users, signage	Effects of trampling & spreading Chytrid-handout for backcountry users, signage	–
Partnerships	Direct work w/fish & game agencies	Hydrologic Alterations	Work with Utah DWQ	BLM allotment managers	Grand Canyon Wildlands Council	–	–	–
Zoning & Planning	–	–	–	–	–	–	Visitor use limits	Spatial limits on visitor use
Law Enforcement	–	–	–	–	–	–	–	–
Laws, Policies & Guidelines	NPS-wide policy directives	–	Improved conditions due to coal-fired plant closures	–	–	–	Continued increase in visitation	Threatened or endangered species listing

Table D-7. Responses for fishes.

Action Category	Primary Driver or Stressor Emphasis						
	Climate Change	**Upland Activities**	**Pollution**	**Non-natives**	**Disease & Parasites**	**Visitor Use**	**Other**
Research, Monitoring, & Inventory	Monitor water temperature, extent of habitat w/ ample flows	–	–	What will replace tamarisk? Grass carp populations	Research on warm-water fish disease or parasites	–	Monitor nongame fish populations
Education & Interpretation	–	–	–	–	–	Interpret protection of important habitat features	–
Partnerships	–	Irrigation flows	–	ERWP, UDWR on monitoring Escalante River	–	UDWR on fishing regulations	UDWR, AZGFD
Zoning & Planning	–	–	–	–	–	Backcountry management plan for Escalante	–
Law Enforcement	–	–	–	Enforce live bait restrictions	–	–	–
Laws, Policies & Guidelines	–	–	–	–	–	Require anglers to keep catfish	Potential listings if steep population declines

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 608/180297, April 2022

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525