



Devils Hole Pupfish Strategic Plan

Phase 2 – Guidelines for Management Practices at Devils Hole, Death Valley National Park

Natural Resource Report NPS/DEVA/NRR—2022/2345



ON THE COVER

Devils Hole pupfish (*Cyprinodon diabolis*) at the Ash Meadows Fish Conservation Facility (©OLIN FEUERBACHER).

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Contents

	Page
Figures.....	v
Tables.....	v
Executive Summary	vi
Acknowledgments.....	vii
List of Acronyms	viii
Rationale	1
Purpose.....	2
Population Size Trends	3
Background.....	3
Increasing Population Size	6
Potential actions:	6
Stable population size.....	10
Potential actions:	10
Declining population size	10
Potential actions:	11
Extirpation	11
Potential actions:	11
No population trend.....	11
Potential actions:	11
Fish condition	11
Potential actions:	12
Egg collection.....	14
Maintain current egg collection levels:	15
Increase egg collection:	15
Decrease egg collection:	16
Salvage adults:.....	16

Contents (continued)

	Page
Genetic condition at the AMFCF:	16
Habitat Condition.....	17
Background.....	17
Temperature.....	17
Potential actions:	18
Dissolved oxygen (DO).....	19
Potential actions:	19
Water volume and depth over the shallow shelf	19
Potential actions:	20
Algal standing mass (biomass) and nutrients	20
Potential actions:	21
Benthic boundary layer.....	21
Potential actions:	21
Macroinvertebrates.....	21
Disturbance Events	23
Background.....	23
Flash flooding.....	23
Potential actions:	24
Seismic events	26
Potential actions:	27
Human caused	27
Potential Actions:	27
Conclusion and Future Directions.....	29
Literature Cited	30

Figures

	Page
Figure 1. Devils Hole pupfish (<i>Cyprinodon diabolis</i>) counts in Devils Hole during biannual spring (gray line) and fall surveys, (dark gray line), 1972–2019	3
Figure 2. Conceptual depiction of risk of extinction for the Devils Hole pupfish (<i>Cyprinodon diabolis</i>) in Devils Hole, NV, relative to counts	4
Figure 3. Conceptual diagram of egg collection of Devils Hole Pupfish (<i>Cyprinodon diabolis</i>) relative to abundance.	15
Figure 4. A) Water surface image of Devils Hole showing location of the shallow shelf and deep pool; B) Underwater image of Devils Hole looking to the southwest in an upward orientation.	18

Tables

	Page
Table 1. Population change scenarios and management actions for Devils Hole pupfish	7
Table 2. Fish and habitat condition parameters and management actions for Devils Hole pupfish.....	13
Table 3. Devils Hole disturbance event scenarios and management actions.	25

Executive Summary

Over the last decade, the population of Devils Hole pupfish (*Cyprinodon diabolis*) has ranged in size from 35 to 187 observable fish. Managing agencies have implemented a number of management actions to conserve this iconic species including habitat manipulations, captive rearing efforts and research projects on the Devils Hole ecosystem. The managing agencies recognize the need for a strategic framework to identify and implement appropriate actions based on real-time ecological conditions and the best available science. Phase 1 (Hausner, 2017) of the Devils Hole Pupfish Strategic Plan provided a review of ecological stressors and past management efforts, and identified data and knowledge gaps that should be addressed in the future. Phase 2 of the Devils Hole Pupfish Strategic Plan provides managing agencies with guidance to efficiently respond to changes in Devils Hole pupfish health and population size, as well as changes to habitat conditions in Devils Hole. Through the development of scenarios related to Devils Hole pupfish population dynamics and habitat conditions, a set of triggers and actions are defined to assist managing agency personnel in critical evaluations of current conditions prior to implementing appropriate actions.

Acknowledgments

The development of the Strategic Plan Phase 2 results from collaboration among the partner agencies working to conserve the natural resources at Devils Hole and the Devils Hole pupfish. The plan was developed and co-written by representatives of the National Park Service, U.S. Fish and Wildlife Service, and the Nevada Department of Wildlife, and would not have been possible without significant contributions from our respective agencies, and common dedication to this unique resource. Agency staff thank Gary Garrett, Brian Healy, Megan Osborne, Steve Parmenter, Josh Rasmussen, and Melissa Trammell for their constructive reviews of an earlier version of this document.

This plan is dedicated to Lee Simons who spent the final years of his career advancing the conservation and recovery of the Devils Hole pupfish and its ecosystem.

List of Acronyms

AFDM:	Ash-free dry mass
AMFCF:	Ash Meadows Fish Conservation Facility
CTM:	Critical thermal maximum
DEVA:	Death Valley National Park
DH:	Devils Hole
DHP:	Devils Hole pupfish
DO:	Dissolved oxygen
ELS:	Early life stage
ERM:	Egg recovery mat
GOES:	Geostationary operational environmental satellite
ICT:	Incident Command Team
LTEMP:	Long-term Ecosystem Monitoring Plan
N:P:	Nitrogen to phosphorus
NPS:	National Park Service
SCUBA:	Self-contained underwater breathing apparatus
USFWS:	U.S. Fish and Wildlife Service
WL:	Water level

Rationale

Over the last half-century, the maintenance of various desert fish populations, both natural and human-supported, has depended on timely intervention (Pister, 1990). In dire circumstances, efforts to avoid extinction depend on management agencies' ability to act quickly and efficiently. However, the management history of the Devils Hole pupfish (DHP) has often been reactionary, with various crises requiring managers to make quick decisions in the absence of strong supporting evidence. Thus, the management agencies recognize the need for a guidance document to support decision-making in crisis situations and respond to changing conditions effectively, reducing the probability that they will develop into crises. This document, referred to as the Strategic Plan Phase 2, fulfills this need, and represents the collective knowledge of the Devils Hole Incident Command Team (comprised of National Park Service, U.S. Fish and Wildlife Service, and Nevada Department of Wildlife representatives; hereafter "ICT"). Guidance provided in the Strategic Plan Phase 2 follows the Strategic Plan Phase 1, a companion document that provides a history of management actions, their ecological outcomes, and the identification of key data gaps (Hausner, 2017).

Purpose

This document is intended to be a guide for managers that generally focuses on the mitigation of demographic threats due to ecological change. Specifically, the document identifies “scenarios” that are causes for concern and may require management action. The scenarios are based on the DHP population size and habitat conditions in Devils Hole (DH) and aim to identify potentially harmful circumstances as they develop. This document also offers a suite of potential responses and management actions based on the best available science. Each scenario includes triggers that indicate when potential management actions may need to be initiated. A list of considerations was developed for each scenario to provide context for the evaluation and implementation of management actions. Implementation of any of these actions may vary depending on specific conditions, as well as our evolving understanding of the biology of the Devils Hole pupfish and its ecosystem.

It is important to recognize the limitations of this document. First, the potential actions described herein represent a starting point from which biologists and decision-makers can engage in discussion, which may deviate from a classical, cause and effect style strategic plan. Additionally, certain potential actions that may involve take of DHP exceeding levels previously approved by U.S. Fish and Wildlife Service may also require review by the DHP Management Oversight Team and further approval by U.S. Fish and Wildlife Service prior to implementation. Finally, the ICT recognizes the ongoing concerns about low genetic variation in the population, and the need to address the genetics of the population in a formal genetic management plan.

Population Size Trends

Background

The most critical variable for consideration of management actions is the DHP population size. Standardized population surveys, hereafter referred to as “counts”, have been conducted in the Spring (March/April) and Fall (September/October) since 1972 with some exceptions. This visual census method, consisting of simultaneous SCUBA and surface surveys, provides an estimate of total abundance (Hillyard et al., 2009). Visual census of Devils Hole pupfish is preferred over other methods to avoid handling stress and to evaluate the variety of microhabitats (e.g. rocky crevices, dense algae mats) that they occupy. Despite the difficulties in estimating population size in this unique environment, counts have shown that total abundance fluctuates seasonally based on habitat conditions. Over the entire period of record (1972–present; Figure 1), Spring and Fall abundance estimates have varied from 35 to 544 fish and, for most of that period, fall counts were higher than spring counts conducted in the same year.

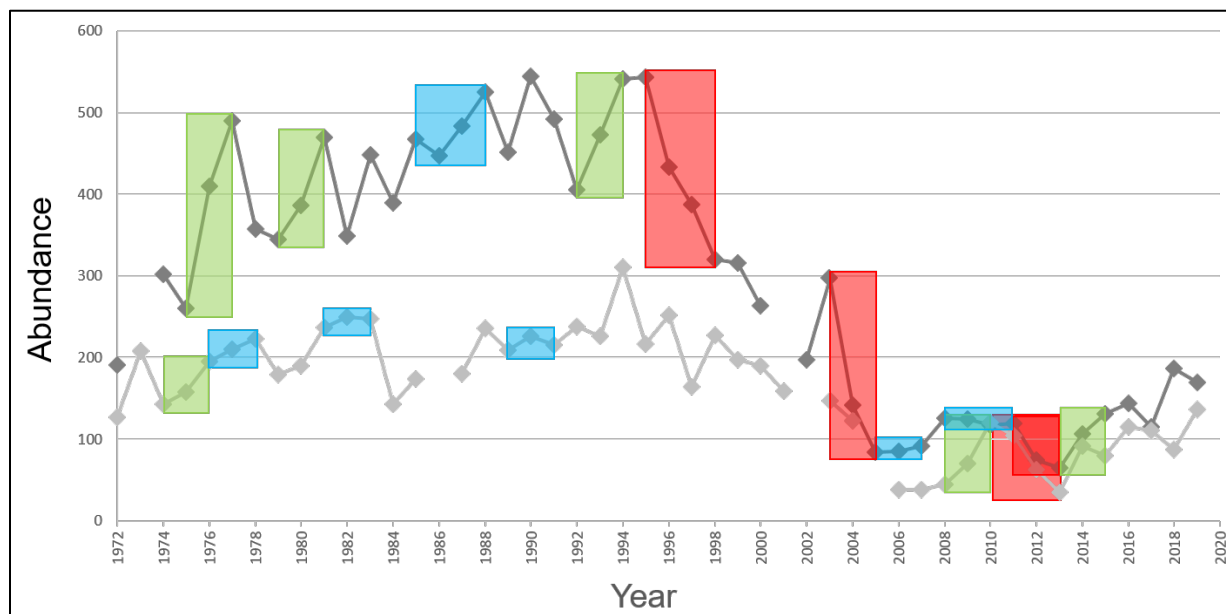


Figure 1. Devils Hole pupfish (*Cyprinodon diabolis*) counts in Devils Hole during biannual spring (gray line) and fall surveys, (dark gray line), 1972–2019. Colored boxes show periods of consecutive counts defined as increasing (green), stable (blue) and decreasing (red) as described in Table 1.

Comparisons to historical data suggest that the current population size is suboptimal. The highest counts for the period of record occurred prior to 1996; whereas counts in recent years have been considerably lower and typically fluctuate around 100 fish. Specifically, the average value for the fall count was 444 (316 to 544) during years 1980–1999, a period when the population was generally believed healthy, compared to an average of 142 (65 to 297) from 2000–2019. A similar pattern was observed for spring counts. The management agencies consider the 3-fold reduction from historical population sizes to likely reflect human-induced changes to habitat, although specific drivers and their relative influences are not clearly understood. There are several hypotheses that are supported

by various lines of evidence. These include changes in the environment affecting water quality (e.g. temperature, dissolved oxygen), physical habitat availability, ecological productivity, food availability, and the loss of genetic variation through bottlenecks in population size. Hypotheses are not mutually exclusive and, in some cases, may be interdependent. The number of hypotheses, complexity, and synergistic effects render biological understanding of the population dynamics a formidable challenge.

Population size is a concern due to the well-established inverse relationship between population size and risk of extinction (Figure 2). Specifically for the DHP, natural stochastic events such as flooding and earthquakes periodically reduce population size through mechanical disturbance, as does carbon availability in the ecosystem. The resulting changes in population demography also effect genetic variation in the population. The management agencies have not identified a specific, optimal population size for the DHP in Devils Hole, but a recovery plan for endangered and threatened species of Ash Meadows, NV which included the Devils Hole pupfish specifically states that the population of this species must be greater than 300 during winter and 700 or greater in late summer and early autumn in order for the species to be downlisted (USFWS, 1990). How realistic these population targets are is unknown at this time. Data from an energetics study of the Devils Hole ecosystem suggests a possible carrying capacity of 600–1,000 DHP based on allochthonous and autochthonous energy estimates (K. Wilson, pers. comm., 2021) but the study did not formally estimate carrying capacity due to missing microbial energetic data (Wilson and Blinn, 2007). In the absence of a target population size, identifying trends in population size is important in determining whether management actions are warranted. For the purposes of this plan, a population size trend is defined by three counts, conducted in the same season of consecutive years with one exception in the case of a >50% year to year decline. To be an increasing or decreasing trend, the difference between counts must be at least 10% and the overall difference between the first and the third count must be at least 20%. Additionally, small populations that are not changing in size may also require management actions. Thus, we define a stable population as changing by less than 10% annually between 3 or more fall counts. This criteria can be applied to historical data to identify specific periods during which the population was increasing, decreasing or stable (Figure 1). These thresholds are intended to accommodate uncertainty and meet the need for timely response to declines that put the population at risk. In addition to trends in population size, the absolute size of the population plays a role in these recommendations. For instance, the management actions considered when the population is increasing/decreasing but remains below 100 may be different than those considered when the population is increasing/decreasing and is over 300.

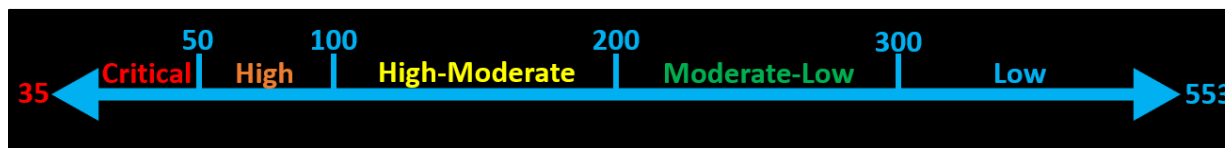


Figure 2. Conceptual depiction of risk of extinction for the Devils Hole pupfish (*Cyprinodon diabolis*) in Devils Hole, NV, relative to counts. 553 and 35 are high and low counts for the period of record (1972–2019).

A number of management actions have been implemented to increase population size. Supplemental feeding began in January 2007 in an attempt to mitigate the impacts of low productivity and limited food supply. The initial feed used from 2007–2013 consisted of a dry flake food specially formulated by Southwest Native Aquatic Resources & Recovery Center for the Rio Grande silvery minnow. The supplemental feed was switched to a crustacean mix containing a more balanced fatty acid profile in Fall 2013. This action was taken after the population again fell to under 40 fish in Spring 2013 and several individuals displayed emaciation and disease condition characteristic of stress, presumably from food or nutrition limitations. The current supplemental feed is a radiation-sterilized, commercially-available feed for aquarium fishes that is comprised of *Mysidopsis*, *Daphnia*, and *Chironomid* bloodworms (Bio-Pure®; Hikari© Sales U.S.A., Inc; Hayward, CA). This mixture is hand-dispensed over the shallow shelf twice per week at 6% estimated population biomass each feeding. There is some evidence that supplemental feeding has contributed to increases in population size (K. Wilson, pers. comm., 2021). Since 2013, managers have also attempted to address deficiencies in cover and organic matter by introducing discrete packets of woody debris on the shallow shelf. “Cover packets” are typically deployed in quantities of 3–6, each measuring approximately 30 cm diameter × 15–30 cm tall. Initial designs consisted of plastic aquarium plants affixed to artificial bases. These were later replaced with local plants such as white bursage (*Ambrosia dumosa*) weighted with rocks to avoid the introduction of unnatural litter when cover packets are inevitably swept off the shallow shelf during flash-floods and earthquake induced seiches (oscillations in the water level creating an effect similar to waves). The three-dimensional structure promotes growth of algae, especially the green alga *Spirogyra*, in the water column and at the water surface. *Spirogyra* is thought to be a beneficial food source for the DHP and provide habitat structure for invertebrates. Micro-temperature and dissolved oxygen measurements taken in 2015–2016 additionally suggest surface mats and pockets of water formed within the vertical and surface algae are subject to convective cooling (Hausner, 2018). Fish, particularly early life stage fish, have been observed utilizing these areas which may serve as thermal as well as structural refuge, however, the explicit effects on population size are unknown. Supplemental feeding and cover augmentation are believed to offset secondary impacts of broader ecosystem changes and are considered temporary until those changes are identified and addressed. An additional management action that has been implemented is the removal of fine sediment from the shallow shelf, which addresses the direct impact of sediment deposited by inflowing storm runoff. Deposited sediments bury or remove algae, reduce habitable space in the water column over the shelf, degrade the substrate for egg incubation and larval rearing, and may increase water temperatures during the summer; potentially causing adverse impacts on eggs and early life stage fish. The scale and scope of sediment removal has been based on post-runoff habitat assessments and are thought to reduce but not eliminate negative impacts on the DHP population.

Concurrent with management of Devils Hole, a refuge population is maintained at the Ash Meadows Fish Conservation Facility (AMFCF) to guard against extinction in the event of stochastic loss of the DHP in Devils Hole. This refuge population is, at present, maintained by natural reproduction and the ongoing transfer of eggs from Devils Hole. The removal of eggs from Devils Hole is a multi-faceted adaptive management decision, the details of which are provided below in the Egg Collection

Plan section. However, other than the removal of eggs, the management guidance contained in this document applies primarily to the wild population in Devils Hole.

Given the dynamic ecology of Devils Hole and the gaps in technical knowledge associated with this unique species, all potential actions identified in the sections below are considered subject to adaptive management. Decisions on which actions to implement will be based on current and future understanding of the factors influencing population dynamics.

Increasing Population Size

Counts of DHP in Devils Hole have not exceeded 200 fish since 2004 (Figure 1). Agency biologists believe that a count of 200 or more fish would be indicative of a significant improvement in population health and safeguard against natural fluctuations in population size. The trigger for considering changes in management actions in response to an increasing population is a fall count of at least 200 fish followed by two additional, consecutive fall counts, each at least 10% greater than the previous (Table 1).

Additional actions and considerations would be triggered in the event of the population reaching 300 fish based on the most recent fall count.

Potential actions:

Curtailing supplemental feeding and habitat enhancements will be considered if the population reaches at least 200 observable fish and continues to increase as described above. This would mark a shift from the more active management of Devils Hole that began in 2007 to a paradigm that relies on the naturally functioning ecosystem to support the population. Phasing out these management actions will be approached adaptively. Any changes to management actions will be closely monitored to consider habitat conditions, population dynamics and to assess effects on population growth.

Managers will also consider increasing egg collection to establish a second refuge population, as required by the Recovery Plan, if agency consensus identifies suitable resources and capacity to maintain another population. Total egg collection over the course of a year would not exceed a number commensurate with ensuring the persistence and sustainability of the source population.

Intrusive research and monitoring strategies such as gut content analysis or fin clipping for genetic analysis are currently not employed due to potential stress on the small population. However, if the population is increasing and counts exceed 300 fish, the managing agencies will consider more intrusive research strategies to answer questions that are critical to management. This may include destructive tissue sampling and/or handling of DHP from Devils Hole. Untested habitat enhancements may also be considered in this scenario to test the viability of these actions.

Table 1. Population change scenarios and management actions for Devils Hole pupfish. Items with an asterisks are considered experimental.

Scenario	Definition/Description	Population Size	Considerations	Potential Actions
Population Increasing	Fall count of at least 200 fish followed by two additional fall counts each 10% greater than the previous	>200 observable fish	- Population size - Duration of trend - Fish condition - Habitat condition (see Table 3)	1. Reduce or terminate enhancement actions: feeding, habitat augmentation (e.g. cover packets) 2. Translocate eggs to another site (e.g. AMFCF)
	Three fall counts with 10% increases and a final count of over 300 fish	≥300 observable fish	- Population size - Duration of trend - Fish condition - Habitat condition (see Table 3)	More intrusive research (e.g. fin clips, gut analysis) will be considered when the population reaches 300.
Population Stable	Counts vary by less than 10% annually over the course of three consecutive fall counts	<100 observable fish	- Population size - Duration of trend (i.e. how long with no population growth) - Fish condition - Habitat condition - Viability of refuge population - ELS Abundance (<12 mm) fish - Genetic diversity	1. Increase or enhance feed 2. Enhance habitat (see Table 3) 3. Predator management
	—	>300 observable fish	—	1. More intrusive research (e.g. fin clips, gut analysis) will be considered when the population is stable at 300 or above. 2. Conduct research to determine viability of habitat enhancement techniques.

Table 1 (continued). Population change scenarios and management actions for Devils Hole pupfish. Items with an asterisks are considered experimental.

Scenario	Definition/Description	Population Size	Considerations	Potential Actions
Population Declining	Abundance decreases by 10% per year for two years as indicated by three consecutive fall counts or three consecutive spring counts or abundance decreases by 50% over the course of one year as indicated by two consecutive fall or two consecutive spring count.	>100 observable fish	- Population size - Population structure (observable size classes) - Sex ratio - ELS Abundance (<12 mm) fish - Duration of trend - Fish condition - Habitat condition - Genetic diversity	1. Modify supplemental feeding program 2. Introduce organic matter or fertilize 3. Changes to ERM schedule 4. Increased observations and documentation. 5. Increase or enhance cover, including introducing floating mats to simulate floating <i>Spirogyra</i> mats. 6. Temperature (measures to cool/moderate shelf temperature).* 7. DO (increase concentration using bubblers or similar).* 8. Introduce food items from AMFCF (ostracods, <i>Spirogyra</i>).*
	Abundance decreases by 10% per year for two years as indicated by three consecutive fall counts or three consecutive spring counts or abundance decreases by 50% over the course of one year as indicated by two consecutive fall or two consecutive spring count.	<75 observable fish	- Population size - Population structure (observable size classes) - Sex ratio - ELS Abundance (<12 mm) fish - Duration of trend - Fish condition - Habitat condition - Genetic diversity	Dependent on habitat conditions and approval of supplementation strategy consider supplementation with live individuals from AMFCF, assisted rearing of eggs collected from DH, or evacuation of some fish to AMFCF

Table 1 (continued). Population change scenarios and management actions for Devils Hole pupfish. Items with an asterisks are considered experimental.

Scenario	Definition/Description	Population Size	Considerations	Potential Actions
Population Declining (continued)	–	<30 observable fish	• Population size • Population structure (observable size classes) • Sex ratio • ELS Abundance (<12 mm) fish • Duration of trend • Fish condition • Habitat condition • Genetic diversity	Dependent on habitat conditions and approval of supplementation strategy consider continued supplementation, assisted rearing, or evacuation of remaining individuals.
Potential Extirpation	No observable fish in DH	–	Status and condition of AMFCF fish	1. Implement an inclusive evaluation to determine whether extirpation occurred (SCUBA visual census, trapping, eDNA). 2. Evaluate and determine likely causes of extirpation. 3. Reintroduction of AMFCF fish into DH if conditions allow.
No trend	Current trend meets none of the conditions outlined above	Any	–	Actions considered based on current habitat conditions and population size

Stable population size

The population will be considered stable when counts vary by less than 10% annually over the course of three or more fall counts in consecutive years. When the population is stable, management decisions and actions will be based on total abundance as indicated by the counts. Management actions in this scenario will be considered when the count in the third year is either fewer than 100 fish, or more than 300 fish. In the past, management actions have responded to either declines in population size (indicated by counts), or to specific events that abruptly altered habitat, particularly storm water inflow and seiches generated by seismic events. However, a smaller population is at greater risk of extirpation for a variety of reasons, even if it appears to be stable. For example, small populations are increasingly vulnerable to changes in resources, which directly affect seasonal abundance, as well as stochastic events that potentially drive the population precariously close to extinction (e.g. fall 2013; Table 1).

A small, demographically stable population presents genetic challenges as well. Small populations lose genetic variation at a faster rate compared to larger populations via genetic drift. As such, DHP population size, which has remained at approximately 100 animals in recent years, (2014–2019) is of concern. Thus, it is important to determine whether action to increase the population is warranted when the population remains stable and small for an extended period.

Potential actions:

Potential actions in response to a stable population <100 individuals include changing supplemental feed (e.g. increasing the feeding rate, altering the feed formula), habitat manipulation or enhancement, water temperature mitigation, predator management, and genetic management (see below). If the population remains stable but counts exceed 300, the population may be considered robust enough to allow more intrusive research and monitoring strategies that have not been implemented in recent years due to low DHP counts. These strategies may include handling and/or destructive tissue sampling (e.g. gut content analysis, fin clips etc.) of DHP from Devils Hole. Additional habitat enhancement actions may be implemented on an experimental basis in the event that the population exceeds 300 fish.

Declining population size

A declining population trend is considered to occur when abundance decreases by at least 10% per year over three consecutive fall counts or three consecutive spring counts. That is, a count (regardless of absolute number or season) followed by two additional counts each at least 10% lower than the previous. The population will also be characterized as declining if abundance decreases by 50% over the course of one year as indicated by two consecutive fall or two consecutive spring counts (Table 1). A spring to fall difference of 50% or greater might also be considered a decline. Different actions may be warranted depending on population size as indicated by the most recent count (see Table 1).

Since the population could meet the definition of declining based on either Fall or Spring counts it is possible that the population might meet the definition of declining based on Spring counts and meet the criteria for a different population trend based on Fall counts. In the event that the population meets multiple trend conditions, the population will be considered declining.

Potential actions:

Management actions considered for declining populations may become logistically difficult with decreasing population size. Potential actions include changing supplemental feed, increasing the feeding rate, habitat manipulation or enhancement, water temperature mitigation, predator management, and genetic management (Table 1). More intensive alternatives such as the repatriation of Devils Hole fish after assisted rearing of eggs or the supplementation from refuge populations might be considered next. If population size and/or habitat conditions suggest the population at Devils Hole is in danger of immediate extirpation, remaining animals may be evacuated to the AMFCF. The potential for this action requires the development of an Evacuation Plan to outline decision processes and protocols. Decisions on which actions to implement will consider population size, current understanding of the biological and physical/chemical factors influencing population dynamics, and the assumed risk of the management action. Some actions could entail substantial risk, including potential supplementation and evacuation of fish from Devils Hole.

Extirpation

For the purposes of this plan, if there are no observable fish in Devils Hole based on the most recent SCUBA visual census the population will be considered potentially extirpated. Actions will be necessary in this event to confirm extirpation, evaluate and determine the cause of extirpation, and to plan for and implement potential reintroduction of DHP.

Potential actions:

Management actions in the event of suspected extirpation should focus on confirmation of extirpation and if needed, evacuation of remaining fish to AMFCF. Efforts to confirm extirpation should be broad and include SCUBA visual census, ELS survey, trapping, and eDNA sampling. Evaluation and assessments of the cause of the extirpation should also be conducted. After a thorough review of causes, current habitat conditions, and considering the status of refuge populations the ICT should begin planning for potential reintroduction. This action will follow a process outlined in a supplementation or reintroduction strategy to be drafted by the ICT.

No population trend

The population will be considered to have no active trend if none of the above population conditions are met. In this case, actions will be considered based on habitat/fish conditions in Devils Hole and overall population size.

Potential actions:

The potential management actions considered in this scenario will be those that are detailed in the habitat and fish condition sections below.

Fish condition

Biologists observe body condition of DHP formally during population counts and informally when visiting Devils Hole for research, monitoring, and management. Individual fish in poor condition are occasionally seen and documented. In the fall of 2006, recognition that a large number of fish were exhibiting symptoms consistent with starvation resulted in initiation of a supplemental feeding effort in January 2007. The feeding program continues to be implemented. Poor condition in fish may

indicate inadequate diet, atypical environmental stress, and/or disease. A decision to take any specific action will be based on all available evidence and may include analyses of environmental data and/or testing for pathogens. Several pathogens have been identified in DHP held in captivity at AMFCF and are presumed to have been carried by material from Devils Hole. These include bacterial pathogens such as *Mycobacterium* sp., *Aeromonas* sp., and *Flavobacterium columnare*. These species are common to the region and are not considered to be a large contributor to morbidity and mortality in otherwise healthy pupfish, instead presenting in fish that are stressed or moribund. Parasites including a hexamita-like diplomonad and intestinal round and flatworms have been identified, but their overall impact is unknown. Although they may be considered “normal” residents of Devils Hole, they have the potential to cause mass mortality or otherwise negatively impact fish health, fecundity, and recruitment if given the opportunity. Mutations, horizontal gene transfer, and introduction of novel pathogens likewise have the potential to instigate catastrophic infections. Frequent monitoring of fish condition is of utmost importance to rapidly detect changes in health status and to determine if an underlying environmental shift has stressed the fish or if a new pathogen has emerged.

Potential actions:

Occasional observations of individual fish in poor condition are not considered cause for concern. If the percentage of unhealthy fish is greater than expected or there is an increase in the number of unhealthy fish. (e.g. emaciated, scoliosis, bloated, lesions, etc.), action may be warranted (Table 2). Rapid detection of issues and subsequent identification is critical, particularly if disease issues are suspected. An immediate response, which has minimal negative impacts, would be to increase feeding with a nutritionally complete diet to allow fish to produce a robust immune response. Clearly moribund fish may also be removed, both to facilitate diagnosis, as well as to reduce spread of infections through the water and cannibalism. If fish are exhibiting symptoms consistent with starvation due to lack of natural forage, the supplemental feeding regime can be altered to increase quantity and/or quality of supplemental feed. Responding to diseased fish within Devils Hole is difficult as it is likely infeasible to treat fish for disease in Devils Hole. Diagnosis will provide the best guide to resolution. Rapid diagnosis including basic histology and microbiology can be performed at AMFCF, but such diagnosis will also be in concert with the USFWS California/Nevada Fish Health Center or other experts to fully examine the issues. Medicated feeds may potentially be added to Devils Hole in combination with the existing feeding regime with minimal risk to the ecosystem, depending on diagnosis. These medications will aid recovery, but not entirely eradicate a disease. For non-obligate pathogens, including most bacterial species, this is likely the best that can be done. For obligate pathogens such as viral and some parasitic species, complete eradication is theoretically possible, but would be difficult. In the case of parasites, it would entail removal of all fish from Devils Hole, followed by successful treatment, and reintroduction once the pathogen has disappeared in Devils Hole, absent the host. In the case of viruses, it would entail removal of all fish from Devils Hole and replacement with uninfected fish. A less extreme option may be removal of acutely infected fish, treatment, and reintroduction of these individuals once they have recovered and presumably, an adaptive immune response has developed.

Table 2. Fish and habitat condition parameters and management actions for Devils Hole pupfish.

Parameter	Definition/ Description	Considerations	Potential Actions
Fish Condition	Greater than 5% appear unhealthy: emaciated, scoliosis, blanched coloration, bloat, lesions, raised scales other signs of disease	- Population size - Population trend - Habitat condition - Season/time of year	- Increase or enhance feed - Treat fish for disease - Water quality amelioration (see HABITAT CONDITIONS/ potential actions)
Temperature	>36°C (James 1969) maximum daily temperature over the shelf	- Population size - Population trend - Fish behavior - Spawning success - Duration, location(s), percentage of shelf affected of elevated temperatures - Reproductive output–decreased rate	- Develop/deploy heat exchanger or recirculating water system - Shade cloth to buffer against peak temps - Increase number of cover packets - Deploy water misters to evaporatively cool water on the shelf.
Dissolved Oxygen	Minimum daily DO over the shelf as measured by the sonde Initial low threshold: <1.5 mg/L for 6 consecutive hours on three consecutive days Lower threshold: <1.0 mg/l for 6 consecutive hours on 7 consecutive days	- Population size - Population trend - Fish behavior - Spawning success - Early life stage fish deformity rate - Magnitude and duration of lower DO concentrations - pH	- Increased monitoring - Habitat/substrate modification (remove organic matter) - Install oxygen injection system or similar on shelf
Water volume	Water volume over the shelf is reduced by 15% or more mean adjusted water over the shelf based on mean adjusted depth	- Population size - Fish behavior - Spawning success - Vertical habitat availability for <i>Spirogyra</i>, etc. - Temperature	Remove sediment to increase depth/habitat volume over shelf
Standing mass (biomass) and nutrients	<i>Spirogyra</i> biomass is below 5 g AFDM/m ² and N:P ratio below 25:1 for 3 consecutive June sampling dates Algal biomass; Enhance N:P ratio to achieve 25:1	- Population size - Population trend - Fish behavior - Spawning success - Changes in <i>Spirogyra</i> as indication of thermal stress	- Increase or enhance feed - Augment organic carbon by increasing the number of organic cover packets - Use cover packet management to achieve a N:P ratio of 25:1

Table 2 (continued). Fish and habitat condition parameters and management actions for Devils Hole pupfish.

Parameter	Definition/ Description	Considerations	Potential Actions
Benthic boundary layer	Pore water hydrogen sulfide concentrations >2 mg/l consistently for one year indicating oxic/anoxic conditions at sediment-water interface	• Population size • Fish behavior • Spawning success • Temperature	1. Redistribute/translocate substrate on the shallow shelf 2. Develop/deploy evaporative/recirculating water system

Egg collection

One active and ongoing management action relevant to population size is the collection of eggs from Devils Hole for the purpose of establishing and maintaining a refuge population at the AMFCF. The Recovery Plan for the Endangered and Threatened Species of Ash Meadows, NV specifies maintaining populations of DHP outside of Devils Hole (USFWS, 1990). Egg collection has been carried out since Fall 2013, but the collection strategy, specifically the frequency and timing of collections has changed multiple times. The current permits and protocols include a single monthly collection in all months of the year. While experimental when it began, protocols for collection and rearing are now robust and have been successful. The egg collection diagram (Figure 3) summarizes strategies for the transport of DHP eggs from Devils Hole to the AMFCF and aims to offer guidance on egg collections in scenarios that correspond to various levels of extinction risk (Figure 2). This management action differs from many others because it is based solely on absolute numbers, not increasing or decreasing trends in population size. It is important to note that egg collections are planned to continue on a monthly basis with the number of eggs allowed based on the current population size (i.e. bi-annual Spring counts) and the fecundity estimates of the species (Minckley and Deacon, 1973). Finally, the population size of the captive population alone does not warrant a change in egg collection protocols.

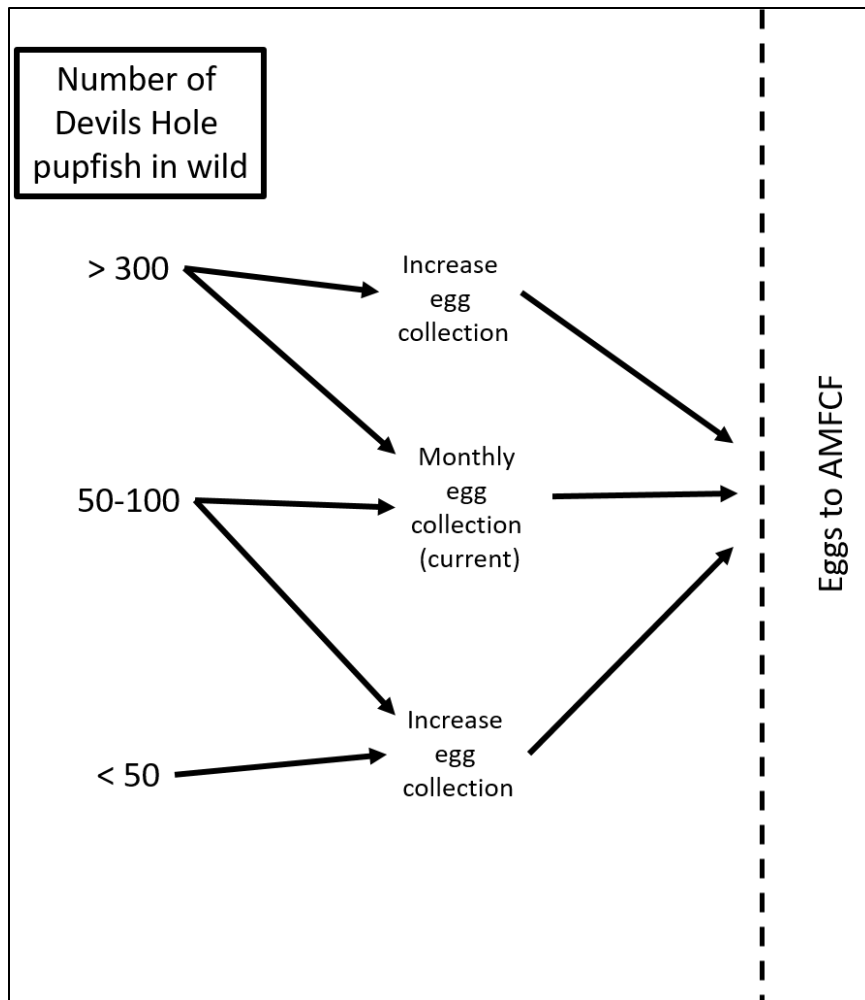


Figure 3. Conceptual diagram of egg collection of Devils Hole Pupfish (*Cyprinodon diabolis*) relative to abundance.

The objective of the egg collection program is to meet recovery goals of establishing additional populations with minimal impacts to the wild population of DHP. The establishment of additional populations guards against extinction, as well as provides a research population for high priority questions about the species' biology. The existence of the AMFCF also provides a rescue option to move remaining fish out of Devils Hole into captivity, in the event that the Devils Hole habitat is compromised.

Maintain current egg collection levels:

Current levels of egg collection (once monthly) are recommended to continue with the objective of retaining gene flow and similar genetics between the captive and wild populations.

Increase egg collection:

Increased egg collection may be recommended if the wild population increases (i.e. >300). In this scenario, additional efforts may support the captive populations with less pressure on the wild

population. However, egg collections potentially influence the habitat and any increase in egg collections would need to be evaluated for impacts to the habitat.

Alternatively, increased egg collections are also recommended if the population in Devils Hole declines (e.g. Devils Hole <100, Devils Hole <50, etc.), presumably in response to poor conditions. The goal of this would be to capture representation of all genetic variation from the wild.

Decrease egg collection:

At this time, reducing egg collection is not under consideration in the interest of maintaining gene flow from the wild to the captive population. Ongoing transfer potentially mitigates population genetic differences associated with variation between habitats and the small genetic effective size in both populations. Reducing egg collection may be considered based on population size in Devils Hole and forthcoming genetic information on the Devils Hole and AMFCF populations.

Salvage adults:

If the population of DHP in Devils Hole declined to precarious levels, egg collection may be discontinued in favor of removal and salvage of adult fish to the AMFCF. Information including the state of the habitat in Devils Hole and the total population size will be used to inform the decision of when to salvage adult fish. Additional analysis is needed to formalize the decision process for this action and an Evacuation Plan needs to be developed to establish protocols for this action.

Genetic condition at the AMFCF:

Another component of fish condition is the genetic health of the population. There is currently no genetic management plan for the wild population of DHP or for the captive population at the AMFCF. Animal translocation, especially in small populations, heightens the consideration for the management of genetic resources. The extant populations of DHP in Devils Hole and the AMFCF are among the smallest for a vertebrate species, and intermittently affected by population bottlenecks over the last half-century (Hausner, 2017). Since 2013, genetic sampling involves collection of tissue for all fish raised in the AMFCF, and represents a tractable approach for monitoring the source population in Devils Hole. However, measuring diversity within the AMFCF is more complex, and requires genetic samples of individuals spawned within the refuge tank. The present monitoring protocol has resulted in larger sample sizes compared to previous work, and genetic studies evaluating genetic diversity and divergence in and between the wild and captive populations are currently underway. Any future genetic results that suggest modifications to egg translocation, or any sections of this Strategic Plan will be considered by the ICT and the appropriate guidance documents will be amended. After sufficient data and analysis, a formal genetic management plan will be developed.

Habitat Condition

Background

Devils Hole is a submerged, limestone cavern that can be divided into a “deep pool” (>150m) and “shallow shelf” (Figure 4). The water’s surface lies approximately 15 m below the land surface creating a window into a deep groundwater aquifer. Conditions on and over the shallow shelf are critical to the life history of the DHP because the habitat on the shelf is used by the DHP for both foraging and spawning. Habitat conditions of Devils Hole that may trigger management actions include both biotic and abiotic processes and parameters that are documented by the Devils Hole Long-Term Ecosystem Monitoring Plan (LTEMP) (Wilson et al., 2009). Biotic processes considered indicators of habitat condition include primary and secondary productivity of algae and invertebrates, respectively. The LTEMP measures algal biomass and macroinvertebrate abundance as surrogates of primary and secondary production. Abiotic parameters considered indicators of habitat condition include water temperature (section 2.5 Strategic Plan Phase 1), dissolved oxygen (DO; section 2.4 Strategic Plan Phase 1), nutrients, water volume over the shallow shelf (section 2.4 Strategic Plan Phase 1), and the benthic boundary layer of the shallow shelf (discussed here in Strategic Plan Phase 2; Table 2). Both biotic and abiotic features of the habitat vary seasonally due to their dependence on solar radiation reaching the water’s surface. Sunlight reaches the shelf in summer for up to 4.5 hours, with no sunlight reaching the shelf from late December through late February (Wilson and Blinn, 2007). Variability in solar radiation influences the food web and subsequently the diet of the DHP (section 2.6 Strategic Plan Phase 1 describes the diet/gut contents of the DHP in more detail), as well as temperature, and DO.

Temperature

Water temperature of the deep pool is approximately 33.5 °C. The shallow shelf temperature is more variable depending on solar radiation and ambient air temperature, and ranges between 32.5°C to 34.5°C as recorded by the water quality sonde located on the southern portion of the shelf. Water temperature on the shallow shelf is also dependent on water depth (i.e. height of water above the benthic substrate to the water’s surface). Hausner et al. (2014) showed that peak daily water temperatures have increased in the last decade, which could be influencing DHP egg hatching success and/or larval DHP survival. Convective mixing models developed by Hausner et al. (2012, 2013) have shown that mean water depth on the shallow shelf regulates heat transfer between the shelf and the surrounding deep pool water. The depth of water over the shallow shelf was also shown to have a stronger effect on temperature than potential impacts from long-range climate change projections (Hausner et al., 2016). While the critical thermal maximum (CTM) for the DHP is estimated at 38°C (James, 1969), the managing agencies believe a maximum daily temperature of >36°C would be detrimental to the fish and warrant consideration of implementing management actions. Therefore, if the maximum peak temperature is >36°C as recorded from the water quality sonde on the southern portion of the shelf, one or more actions described below may be taken (Table 2). However, it is recognized that eggs may be susceptible to harmful temperature effects at lower temperatures. More research is needed to determine whether this criteria needs to be refined.

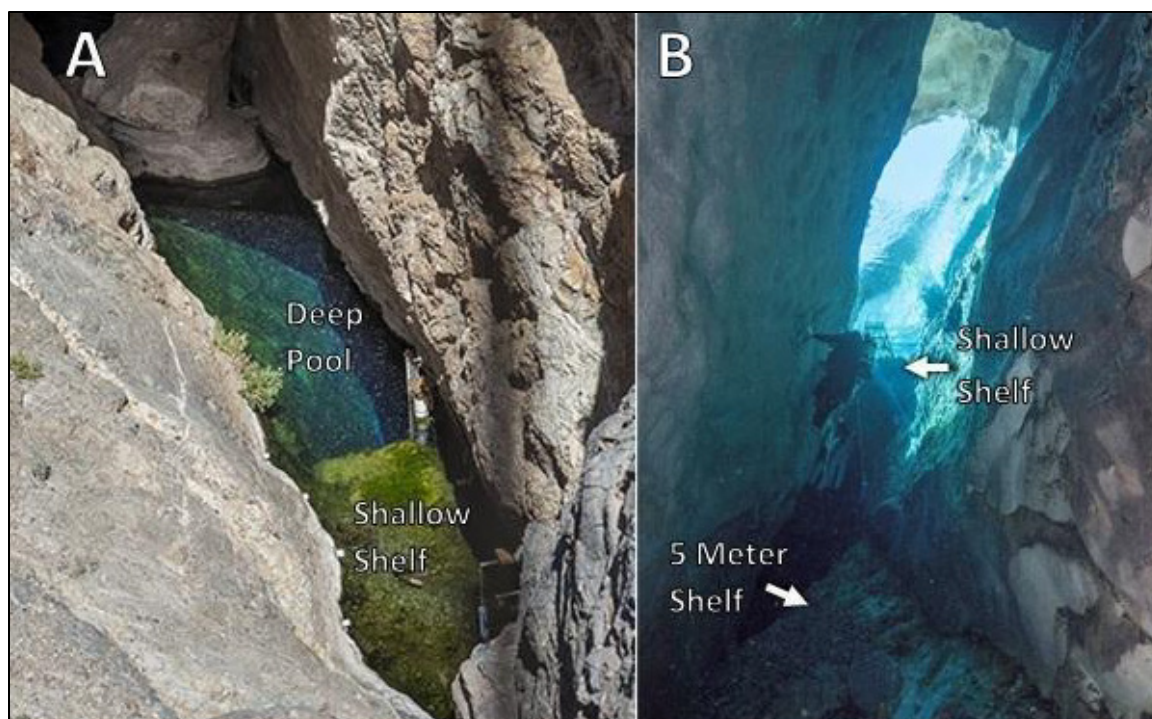


Figure 4. A) Water surface image of Devils Hole showing location of the shallow shelf and deep pool; B) Underwater image of Devils Hole looking to the southwest in an upward orientation. The shallow shelf is located on the opposite side of the diver. The 5 m shelf is a conical debris pile located near the bottom of the image (Credits: Photo A – NPS; Photo B – Brett Seymour, NPS).

Potential actions:

As described by Hausner (2017) in the Strategic Plan Phase 1, cooling water over the shallow shelf is a difficult task due to the constant supply of warm water (33.5°C) from the depths of the submerged cavern. However, it would be possible to develop and deploy a heat exchanger or recirculating water system intended to cool water over the shallow shelf. Considerable infrastructure (e.g. plumbing, heat exchanger, etc.) would be required to continuously remove the 11 kW of heat energy necessary to induce change in water temperature. Another approach could be to recirculate water from the deep pool to the shallow shelf to “cool” the shelf during peak maximum daily temperatures in spring and summer. Critical elements of this action item still need to be determined, including the volume of water required to be pumped from the deep pool to the shallow shelf and the infrastructure required to accomplish this pumping (e.g. size of pump, solar or gas, plumbing). Further research is required to determine the feasibility of this action.

Additional potential actions which require less infrastructure could include use of shade cloths during summer and spring to decrease the amount of solar radiation reaching the shelf, although this could negatively impact algal growth. Increasing the number of cover packets could also be pursued, as these are thought to create pockets of cooler water nearby and surface area for algae to grow and shade water. Installation of water misting devices to induce evaporative cooling of water on the shelf could also be considered but such an action may not be effective at lowering shelf water temperature.

Dissolved oxygen (DO)

Ambient DO concentrations are relatively constant in the deep pool (2.3–3.5 mg/l). In comparison, DO over the shallow shelf is more variable as it is influenced by photosynthesis and respiration, which are influenced by the amount of solar radiation reaching the shelf. DO concentrations in the water column above the shallow shelf range between 1.5–8.0 mg/l, peaking midday during the summer due to photosynthetic activity and decreasing at night when algae respire. Bernot and Wilson (2012) described DO concentrations over the shallow shelf of Devils Hole. Over a two-year study period, water column DO over the shallow shelf ranged between 1.9–6.5 mg/L (Bernot and Wilson, 2012). A dramatic increase in heterotrophic microbial biomass would be necessary to reduce DO to <1.9 mg/L, especially during daylight.

More research is needed on the effects of hypoxia on DHP survival and development. Levels below 1.0 mg/L for extended periods are likely to affect egg development based on work in other systems (Shang and Wu, 2004). For dropping DO levels there are two triggers, a threshold of 1.5 mg/l in which additional monitoring is considered, and a lower trigger of <1.0 mg/l in which actual habitat actions may be necessary (Table 2).

Potential actions:

If DO values, as measured by the water quality sonde on the southern portion of the shelf fall below 1.5 mg/L for 6 or more hours on 3 consecutive days, managing agencies will consider increasing monitoring frequency for DO on the shelf. Surveying ELS fish for potential increased malformation rate will also be implemented if DO levels fall below the 1.5 mg/L threshold. If DO values fall below 1.0 mg/L for 6 or more hours on 7 consecutive days, the agencies will consider removal of organic matter and installation of an air injection system to increase DO values to typical historic levels. Installation of air injection would be experimental and could have unintended consequences that could further stress fish (e.g. pH fluctuations) so pursuing such an action should proceed with caution.

The oxygenation of water on the shallow shelf was previously proposed to increase recruitment through mitigation of the effects of high temperatures on egg development (Hausner, 2017). Oxygenation might also be considered if DO values on the shallow shelf fall below relevant threshold values for extended periods. Oxygenation is more feasible than cooling the water, but there are still complications associated with this action (Hausner, 2017). An initial action of removing accumulated organic matter should be considered before installation of air injection systems. Special infrastructure would be required to inject air at the sediment water interface to increase DO where DHP eggs are deposited during spawning.

Water volume and depth over the shallow shelf

Water depth and volume over the shallow shelf influence water temperature, DO to some extent, and the amount of available habitat for DHP and invertebrates. Water depth is defined as the distance from the top of the water column to the top of the substrate on the shallow shelf. Water depth is regulated by changes in groundwater levels, earth tides, barometric pressure, the deposition of material on the shelf from flood events, and through earthquake induced seiches which remove material from the shelf. There are two ways in which water volume is calculated over the shallow

shelf. First, a point in time water volume uses water depth that is standardized to a specific predetermined water level, so that all water volumes are comparable. The point in time water volume calculation is used to determine changes in habitat size due to changes in the substrate. Slow accumulation of material on the shelf through natural deposition of material falling into and on the shelf also plays a role. Depth measurements, standardized to a single water level, are made in association with substrate composition surveys, which are conducted annually in January and following major disturbance events. Second, water volume is calculated using time series water level data (e.g. monthly, quarterly, and annual mean water levels). The federal government has monitored water level and water level fluctuations in Devils Hole since 1956. From 1990 to 2018, this monitoring has been overseen by DEVA Aquatics and Hydrology program staff and the NPS Water Rights Branch of the Water Resources Division. In 2018, the U.S. Geological Survey in coordination with DEVA hydrology staff has taken over this monitoring effort. The USGS has two systems in place at Devils Hole. The primary datalogger/transmitter records water level (WL) and temperature every 15 min and is programmed with an event "alarm" that is triggered by a WL change of 0.015 ft (0.004 m) or greater within 5 s, which triggers 5 s recordings until the rate of change decreases back below 0.015 ft/5 s. The secondary system records WL and temperature every 15 s. The time series water volume calculation is used to estimate changes in habitat size due to water level.

Agency staff will consider taking action if water volume over the shallow shelf is reduced by 15% or more (Table 2). The reference point for a 15% reduction in water volume is based on point in time as well as time series water level data.

Potential actions:

If it is determined that material needs to be removed from the shelf, it will be transported/relocated via SCUBA to the 5m shelf.

Algal standing mass (biomass) and nutrients

Productivity is assessed through indirect measures of biomass. Algal biomass as g ash-free dry mass (AFDM) is collected every other month as part of the Devils Hole LTEMP. This sampling regime provides trends of the amount of carbon present on the shallow shelf from dominant algae (*Spirogyra* sp. and filamentous cyanobacteria). *Spirogyra* biomass is highly variable over time. For June samples collected between 2011 and 2016, biomass ranged between a low of 5.4 ± 1.6 g AFDM/m² in June 2016 to a high of 27.1 ± 5.6 g AFDM/m² in June 2015.

Nutrient concentrations are also measured every other month as part of the LTEMP. Nitrate, nitrite, ammonia, total phosphorus, sulfate, and hydrogen sulfide are sampled in triplicate over the shallow shelf. Trend analyses of nitrogen species (nitrate, nitrite, and ammonia) and total phosphorus concentrations collected sporadically in the 1980s, 1990s, and mid-2000s have shown that N:P has declined over this period (Archarya et al., 2009). In the mid-1980s and early 1990s N:P was approximately 85:1 (U.S. Geological Survey, unpublished data). This ratio had shifted to approximately 25:1 by 2007–2008 (Archarya, unpublished data). Based on a September 2017 US Geological Survey water quality analyses, N:P ratio remains at approximately 25:1. These data suggest that Devils Hole has become more oligotrophic (decline in nitrogen) over the last several decades.

Allochthonous carbon is an important carbon source for the Devils Hole food web in winter (Wilson and Blinn, 2007). An upland plant restoration project was initiated in May 2017 for the purpose of restoring surrounding areas of Devils Hole that were denuded of vegetation as early as 1950. Dominant plants were planted in the autumn of 2018 with the intent of increasing allochthonous carbon into Devils Hole and assessment of this action is ongoing. Cover packets consisting of local vegetation have also been deployed on the shallow shelf on several occasions in response to earthquake induced seiches removing all organic material off of the shallow shelf. While these cover packets were placed on the shelf to enhance habitat for smaller-sized fish and to create substrate promoting microbial and algal growth, they also anchor floating algal mats in place above the shelf, and provide beneficial allochthonous carbon as the packets decompose.

Potential actions:

If *Spirogyra* biomass remains below 5.0 g AFDM/m² and N:P ratio is less than 25:1 for three consecutive June sampling dates, managing agencies will consider the following actions: evaluate the supplemental feeding regime for DHP, increase the number of organic cover packets deployed over the shallow shelf, and possibly enhance N:P ratio to achieve 25:1 through cover packet management (Table 2).

Benthic boundary layer

The substrate composition of the shallow shelf ranges from fine silts and clays to bedrock. The LTEMP requires that substrate composition analysis be conducted annually in winter and/or after a disturbance event. Disturbance events include flash floods (deposition of material) or earthquake induced seiches that redistribute and/or remove material from the shallow shelf to deeper portions of Devils Hole. Flooding events have the potential to deposit large quantities of fine sediments onto the shallow shelf. These sediments can create an anoxic boundary layer between lower lying sediments and the water column above. This boundary layer can create conditions that may decrease DHP egg hatching success. Anoxic conditions due to high hydrogen sulfide (H₂S) concentrations can suffocate or be lethal to DHP eggs. Hydrogen sulfide (H₂S) concentrations are measured every other month within the pore-water (5 cm depth into substrate) of the shallow shelf. Pore-water H₂S concentrations measured as part of the LTEMP ranged between below detection to 10 mg/L and is highly variable (mean = 0.9; SD = 1.8 mg/L; Table 2). Action will be considered if the bimonthly mean H₂S concentrations are greater than 2 mg/l (based on variance around the mean) over a one-year period.

Potential actions:

Potential actions include gently disturbing the sediment-water boundary layer to “break” this oxic-anoxic zone, and/or more aggressively disturbing this boundary layer by redistributing substrate on the shallow shelf to remove the anoxic zone. Deployment of evaporative aerators on the boundary layer to restrict anoxic conditions has been suggested. However, logistics (e.g. power) and unintentional negative impacts (e.g. changes in pH) should be experimentally tested prior to implementation in Devil Hole.

Macroinvertebrates

Macroinvertebrate abundance in Devils Hole is spatially and temporally variable, and taxa composition and abundance have changed over time. Continued monitoring and data analyses are

needed to better understand the significance and role of macroinvertebrates to ecosystem and community processes within Devils Hole. Therefore, triggers and potential actions regarding management of macroinvertebrates have not been defined at this time.

Disturbance Events

Background

The DHP and other aquatic species found in Devils Hole have successfully survived a multitude of disturbances over time. The habitat of Devils Hole is influenced by natural and human caused disturbances. Natural disturbances due to rain storm events and earthquakes are variable and are often unpredictable. However, these disturbances can significantly change the habitat. For example, in 2012 there were a total of eight earthquake induced seiches and one flash flood event that significantly disturbed the habitat on the shallow shelf. In 2015, there was only one significant flash flood. In addition to varying in frequency, the intensity of natural disturbance events also varies from unnoticeable to what appears catastrophic.

Human caused disturbances are most worrisome because both the timing and specific type of impact are difficult to predict. Unfortunately, humans have the capability of causing irreversible and detrimental harm to the entire ecosystem. For example, groundwater pumping in the late 1960s through early 1970s from a nearby well led to a decline in water level at Devils Hole. Water levels decreased to a point where a majority of the shallow shelf was exposed. At present, the shallow shelf is submerged; however, the water level is still approximately 30 cm below pre-pumping levels. Over the years, there have also been a number of incidents of vandalism at Devils Hole. While none of those incidents are known to have had significant adverse impacts on the population or its habitat, the potential for such impacts exists. Impacts from exogenous materials or organisms is an additional concern. All persons accessing Devils Hole currently follow a strict decontamination protocol to reduce the potential for the introduction of non-native organisms, fish pathogens, and chemical contaminants into the system (Bower, 2009). Thus far, these measures have been successful in eliminating such threats.

Flash flooding

Rain storms are rare in the Mojave Desert with an average rainfall of 11 cm/yr for Ash Meadows National Wildlife Refuge (Stillings, 2011). The watershed of Devils Hole is approximately two hectares of steep limestone terrain. Major rain events carry organic and inorganic material into Devils Hole altering the substrate composition, topography, and mean depth on the shallow shelf as well as depositing material into the deeper portions of the ecosystem. Winter rains do not typically cause flash floods, but have produced overland flow depositing material on the shallow shelf. Though infrequent, summer monsoons are capable of producing large volumes of rain in a brief period of time. These highly localized and slow-moving systems, combined with dry hydrophobic soils, lead to overland flow and erosion of the landscape.

Flash flood deposits on the shallow shelf can lead to both short- and long-term effects, and flood events are both beneficial and detrimental to the ecosystem. Short-term effects include: 1) an inflow of cooler, highly oxygenated, and nutrient rich water, which may be beneficial to the ecosystem, 2) the displacement or burial of algae, DHP eggs and larvae, and aquatic macroinvertebrates, and 3) localized anoxic conditions caused by the decomposition of deposited organic material. This is detrimental to DHP eggs deposited on the shelf and newly hatched immobile larvae that cannot

relocate to areas with higher dissolved oxygen concentrations. Long-term effects include: 1) decreased water depth and volume leading to more variable and extreme daily water temperature, which will have detrimental effects on any DHP eggs deposited in shallow areas overnight which may not survive midday rises in temperature, 2) an increase in exposed substrate during diel water fluctuations (maximum of 15 cm), which may cause desiccation of eggs deposited while the substrate was submerged but is exposed at low tide, and 3) decomposition of deposited organic matter into basic nutrients benefiting various species within the food chain. Riggs and Deacon (2002) estimate Devils Hole experiences an average of one flash flood event per year. Since 2004, National Park Service (NPS) staff have documented six flash floods that significantly altered the shallow shelf; two were severe enough to prompt management actions.

The most concerning issue for management is water depth and volume over the shallow shelf. These can have the greatest impact on DHP egg development and survival. Also, the deposition of organic material provides needed nutrients to other organisms within the ecosystem. Based on this current understanding of the ecosystem, management response to flash floods in Devils Hole have changed over time:

August–September 2004: Two flash floods occurring on 15 August and 11 September deposited large quantities of material on the shallow shelf. This second flood deposited 1.66 m³ of material on the shallow shelf resulting in a 54.3% reduction in habitat volume. At the time, managing agencies decided to wait and monitor the system until winter. However, on 7 February 2005, after observing extremely low reproductive success during the fall and winter, the managing agencies decided to remove material from the shallow shelf to increase water depth and return the substrate composition to pre-flood conditions. Sediment and organic matter from the shallow shelf were carried out of Devils Hole and piled outside of the fenced area. Removing this material from the Devils Hole ecosystem is now believed to have been a poor choice as the long term-benefits of increased organic material were lost due to this action.

30 June 2016: A flash flood occurred while staff were performing an early life-stage survey in Devils Hole. The weather station at Devils Hole recorded a total of 5.28 cm of rain in a 90 min time-period (3.02 cm in 20 min and 4.09 cm in 40 min). A total of 2.1 m³ of material was deposited on the shallow shelf exposing approximately 1/3 of the shelf to air during low tide. The agencies decided to take a different approach as they felt the removal of the material would change the ecosystem. The recommended action was to remove material only the portion of the shallow shelf prone to desiccation. Sediment was sorted to separate algae and aquatic invertebrates from the inorganic material, then relocated to the 5 m shelf (Figure 2) via SCUBA. This action allowed all of the material/carbon to remain in the ecosystem while increasing available habitat on the shallow shelf for DHP.

Potential actions:

If >15% of the shallow shelf is exposed at low tide, the managing agencies will consider relocating exposed sediment and organic matter to the 5 m shelf via SCUBA. Additionally, if the water volume

over the shelf is reduced by 15% or more due to sediment deposition, managing agencies will consider relocating material from the shallow shelf to the 5 m shelf (Table 3).

Table 3. Devils Hole disturbance event scenarios and management actions.

Scenarios	Definition/ Description	Considerations	Potential Actions
Storm inflow (flash flooding)	Storms that create overland flow depositing sediment on the shelf	- Population size - Population trend - Fish condition - Timing of events: October–February critical for algal growth; spawning seasons critical for egg/larvae - Percent of shelf exposed to air (15% of shallow shelf exposed to air) - Percent reduction in water volume over shallow shelf (15% reduction in water volume over shelf)	Translocate inorganic sediment to the 5 m shelf
Seismic/seiche event	Seismic event produces a seiche that re-sorts/removes sediment/algae on the shelf and/or results in displacement of cover packets and reduction in forage	- Population size - Population trend - Fish condition - Seasonal timing - Change in sediment composition - Residual algae - Reduction in invertebrates/algae in LTEMP, ERM collections - Percent of shelf exposed to air (15% of shallow shelf exposed to air) - Percent reduction in water volume over shallow shelf (15% reduction in water volume over shelf)	1. Replace recover cover packets 2. Increase or enhance feed 3. Redistribute emerged substrate 4. Return organic materials to shallow shelf (algal mats)
Human caused (e.g. toxicant)	Human activity introduces contaminants or alters habitat	- Population size - Population trend - Fish condition - Fish behavior - Fish mortality - Observed changes in habitat, vandalism, etc. - Evidence of contaminants	If extirpation appears imminent, evacuation of remaining fish to AMFCF. 1. Initiate basic water quality analysis 2. Reference habitat condition and population scenario sections of this document and take action as appropriate based on specific scenario 3. Restore habitat 4. Repatriate salvaged fish when conditions warrant.

Seismic events

Ash Meadows (including Devils Hole) is a major discharge area for the Death Valley groundwater flow system that is part of a large regional carbonate aquifer approximately 100,000 km² in area. Temporary changes in discharge rates and water levels in Ash Meadows springs are among the documented hydrological responses to distant earthquakes (Cutillo and Ge 2006; Weingarten and Ge 2014). Devils Hole is a groundwater-filled fracture cavern system with direct groundwater connectivity. This direct connection and the sheer size of the underlying aquifer promote earthquake-induced seiches—a phenomenon in which seismic movements produce oscillations on the surface of enclosed standing bodies of water—such as within the surface pool at Devils Hole. Based on data collected by Death Valley National Park Aquatics and Hydrology program (DEVA) staff and USGS (described above), earthquakes affecting Devils Hole have registered M5.8–8.1 and originated hundreds to thousands of kilometers away in Alaska, Southern California, Mexico, and Central America (NPS–DEVA, unpublished data). Seismic waves may take anywhere from 5 to 50 min to travel through the earth’s crust from the epicenter to Devils Hole. Resulting seiches have ranged from minor water movement, to significant sloshing, to large waves up to approximately 2 m in height that repetitively expose the entire shallow shelf, scouring away algae and aquatic invertebrates, and redistributing sand, gravel, and cobble substrate. Interestingly, local southern Nevada earthquakes centered within about 250 km of Devils Hole appear to have little to no effect on static water level in Devils Hole.

Death Valley National Park staff has documented 18 seiches in Devils Hole from 2012 through April 2018, which removed algae and redistributed substrate on the shallow shelf, an average of about 2.5 events per year (NPS, unpublished data). Disturbance from these events can potentially affect DHP and the ecosystem in several ways. Both earthquake and flash-flood disturbance have been documented to affect DHP behavior (Lyons, 2005), including increases in spawning observed 1–3 days after seiches, possibly attributable to mechanical mechanisms such as water and/or substrate movement, or to temporary changes in water quality, particularly temperature and dissolved oxygen (Chaudoin et al., 2021). Other positive effects may include the removal of fine sediment and detritus, potentially improving sediment chemistry profiles (i.e. reducing ammonia and hydrogen sulfide concentrations) and freeing up interstitial space for habitat utilization by invertebrates or larval fish. Negative effects include temporary reduction in food (i.e. algae and invertebrates) on the shelf. This is of particular concern after fall and winter events, when the lack of sunlight reaching the water surface reduces the rate and quantity of algal regrowth. The potential for impacts to eggs during critical spring and fall reproductive seasons is also of concern, as are impacts to larvae which utilize interstitial spaces and risk being crushed, displaced, or having diminished post-event habitat quality and availability due to interstitial infilling and reduction in micro-organism food resources.

Managing agencies have responded to seiches in the past by mediating their effects. In response to loss of algae, cover packets have been deployed multiple times on the shallow shelf since 2013. In response to reductions in food resources, supplemental feeding regime has been modified. Supplemental feeding was implemented in January 2007 after the population fell to under 40 individuals. Adaptive changes to supplemental feeding in response to seiche impacts have included:

December 2016–February 2017: NPS staff implemented one additional feed-day per week. Supplemental feed for the additional day consisted of Zeigler® Zebrafish Diet dry fish feed (Pentair–Aquatic Ecosystems, Part #AH271; Ziegler Bros.; Gardners, PA) hand distributed on the shelf at 3% estimated population biomass. This action was the result of fish condition assessments following a 08 December 2016 seiche that revealed approximately 5–10% of the population was emaciated, including all younger fish, with a few displaying scoliosis and the overall population appearing abnormally thin.

24 January 2018: NPS staff implemented a single, additional feed-day following a 23 January 2018 seiche that scoured away algae already sparse on the shelf due to overwinter conditions. Staff noted a couple of younger adult fish that appeared already thin and somewhat emaciated. The single additional feed-day, which increased feeding frequency to three times per week the week of 22–26 January 2018, was implemented as a preventative management action to provide temporary relief until natural food sources could begin to recolonize the shelf. The supplemental feeding schedule resumed regular, twice-weekly frequency the following week.

Potential actions:

In response to a seiche event that removes food and cover on the shelf the managing agencies will consider increasing feeding temporarily and replacing or increasing the number of cover packets on the shelf. Other potential actions may include manual redistribution of any emerged substrate resulting from seiche events, and the use of snorkel or SCUBA to collect and return biological materials scoured during seiche events from the deeper habitat back to the shallow shelf.

Human caused

Due to the sensitive and contained nature of Devils Hole, human activities, malicious or otherwise, have the potential to cause significant damage to the ecosystem and the DHP. Site infrastructure has been installed to help prevent malicious acts such as vandalism, fish take, or general trespass. These include a perimeter fence topped with barbed wire, a caged visitor viewing area to prevent people from throwing items into Devils Hole, and a security system comprised of motion sensors, audible alarms, and cameras that record and stream video footage to an offsite location. Despite these preventative measures, the enclosure has been breached and the resource vandalized on at least two recent occasions (2016–2018).

Some ways that human activity may damage the resource include the introduction of contaminants, explosives, or other items that could remove or harm the DHP or destroy the ecosystem. Immediate impacts may be seen by unexplained changes in fish behavior, morbidity, mortality, or habitat condition (e.g. changes in water color, clarity, or smell; drastic changes in the aquatic invertebrate or algal community; or irregular water chemistry profiles).

Potential Actions:

Managing agencies response to trespass, vandalism, or contamination will depend on apparent severity of impact. Initial response to such events may include visually assessing fish health/mortalities and implementing a plan to initiate basic water quality testing (pH, salinity,

chlorine, redox potential, ammonia). Specific responses will vary based on what human caused disturbance occurred and how habitat conditions are altered. The habitat condition and population scenario sections of this document will be referenced to respond to each event. Evacuation of fish may be necessary if an ongoing mortality event is occurring or if habitat conditions have substantially deteriorated. Following the initial disturbance, habitat restoration efforts discussed above may be implemented if necessary. If evacuation occurred, reintroduction planning should occur when the threat to fish in Devils Hole is no longer present. Though outside the scope of this document, the implementation of public outreach programs (in coordination with agency external affairs offices) is a potential preventative tool that may help build local advocacy for conservation of Devils Hole and surrounding resources.

Conclusion and Future Directions

The Strategic Plan Phase 2 is intended to be a guidance document to adaptively manage the DHP and its ecosystem by identifying potential management actions that have been thoroughly vetted with the best science and information available. Current and future agency staff including field personnel, the ICT and Management Oversight Teams, and senior management staff should maintain familiarity with the plan and how it will be implemented, to be best prepared for events and circumstances requiring timely action.

Future directions:

- The Strategic Plan Phases 1 and 2 should be used to guide future applied research that will help fill in data and knowledge gaps.
- Reports and data from the LTEMP and research projects should be incorporated into updating triggers, considerations, and or potential recovery actions.
- The Strategic Plan Phase 2 should be reviewed annually by the ICT and revised as needed, but on no less than a five-year interval to incorporate new data, protocols and potential actions.
- The ICT will develop the following documents: a supplementation strategy, a genetic management plan and an evacuation plan.
- The ICT and partners will implement the actions as described in this document.

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