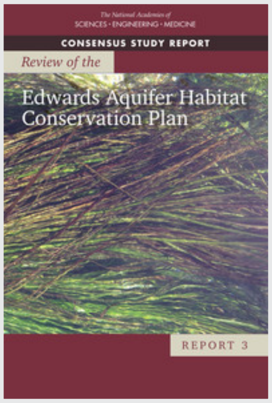


# Review of the Edwards Aquifer Habitat Conservation Plan: Report 3

## DETAILS

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*Review of the*

# Edwards Aquifer Habitat Conservation Plan

REPORT 3

Committee to Review the Edwards Aquifer Habitat Conservation Plan

Water Science and Technology Board

Division on Earth and Life Studies

A Consensus Study Report of

*The National Academies of*
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# Preface

The Edwards Aquifer in south-central Texas is an important water resource that also provides critical habitat for threatened and endangered species in the San Marcos and Comal spring and river systems. The unique habitat afforded by these spring-fed rivers has led to the evolution of species found in no other locations on Earth. Because of the potential for variations in spring flow due to both human and natural causes, the Edwards Aquifer Authority (EAA) and stakeholders have developed a Habitat Conservation Plan (HCP) to protect these unique species. The HCP seeks to effectively manage the river-aquifer system to ensure the viability of the endangered species in the face of future water quantity concerns, such as drought and increased demand from population growth, as well as water quality threats to the system.

The National Academies of Sciences, Engineering, and Medicine were asked by the EAA to assist in this process by reviewing the implementation of HCP activities. The National Academies' study was planned in three phases, with the first phase being a review of the scientific efforts that are being conducted to help build a better understanding of the river-aquifer system and its relationship to the endangered species, including monitoring and modeling. The first phase led to a report published in 2015 that provided an evaluation and recommendations for strengthening those efforts. The second phase led to a report published in 2017 that built upon recommendations in the 2015 report (and the EAA's response to them), as well as evaluating both hydrologic and ecological modeling and the minimization and mitigation (M&M) measures being undertaken for the HCP.

This is the third and final report, which evaluates the likelihood of whether the biological objectives set in the HCP will meet the biological goals and whether the M&M measures will meet the biological objectives. Recognizing that we now have a better understanding of the Edwards Aquifer system as well as the stressors that may impact its condition, the Committee also chose to make recommendations in a final chapter on a path forward that may suggest the need for modifications to the biological goals and objectives. These suggestions are offered in recognition that the ultimate goal is protection of the listed species and not the surrogates for that protection that are identified as biological goals in the HCP.

This study was established under the auspices of the Water Science and Technology Board (WSTB) of the National Academies with the title Committee to Review the Edwards Aquifer Habitat Conservation Program. The Committee included 11 individuals representing expertise in all areas relevant to the statement of task, including the hydrogeology of the aquifer and the chemistry and ecology of river systems. Four meetings were held over the past year. The first two meetings were held in San Antonio and included presentations on current EAA and HCP activities relevant to the Committee's statement of task. I would like to thank the following individuals for giving presentations to the committee during one or more of its meetings: Nathan Pence, Executive Director of the Habitat Conservation Program, EAA; Chad Furl, Alicia Reinmund-Martinez, Jim Winterle, Mark Hamilton, and Mark Friberg, EAA; Jacob Jackson and Ely Kosnicki, BIO-WEST; and Josh Perkin, Texas A&M Department of Wildlife and Fisheries Sciences. We would also like to thank the many people who helped organize and run the field trips taken by the Committee, particularly Nathan Pence, EAA; Ed Oborny, BIO-WEST; Zac Martin, City of New Braunfels; Lindsay Campbell, U.S. Fish and Wildlife Service; and Melanie Howard, City of San Marcos.

Although Committee members represented many diverse perspectives and expertise that varied from river-aquifer hydrology to biology, they reached consensus on all recommendations included in the report. We hope that the EAA will find these recommendations useful as they guide the scientific initiatives designed to provide a solid foundation for effective management of the river-aquifer system and protection of the endangered species.

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report: Stephen R. Carpenter, University of Wisconsin, Madison; Wendy D. Graham, University of Florida, Gainesville; Jessie C. Jarvis, University of North Carolina, Wilmington; Peter Kareiva, University of California, Los Angeles; Paul Mayer, U.S. Environmental Protection Agency; Margaret Palmer, University of Maryland, Annapolis; Chris Phillips, University of Illinois and the Illinois Natural History Survey, Champaign; and Robert G. Traver, Villanova University.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Patrick L. Brezonik, University of Minnesota, and R. Rhodes Trussell, Trussell Technologies, Inc. Appointed by the National Academies, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee.

Danny D. Reible, *Chair*
Committee to Review the Edwards Aquifer
Habitat Conservation Plan

# Contents

# Summary

The Edwards Aquifer in south-central Texas is one of the most productive karst aquifers in the world. Covering an area of approximately 3,600 square miles, it is the primary source of drinking water for over 2.3 million people in San Antonio and its surrounding communities. In addition, it supplies irrigation water to thousands of farmers and livestock operators in the region, which can account for as much as 30 percent of the total water pumped from the system each year. The Edwards has extremely high-yield wells and springs that respond quickly both to rainfall events and to water withdrawals. The region experiences periodic droughts, some of which have been severe enough to drastically reduce flow in the Edwards Aquifer and its major springs (Comal Springs in New Braunfels and San Marcos Springs in San Marcos).

Comal Springs and San Marcos Springs and their river systems house several plants and animals found nowhere else in the world. Eight of these species are listed as threatened or endangered under the federal Endangered Species Act (ESA): the fountain darter, the San Marcos gambusia (which is presumed extinct), the Texas blind salamander, the San Marcos salamander, the Comal Springs dryopid beetle, the Comal Springs riffle beetle (CSRB), the Peck's Cave amphipod, and Texas wild rice. To protect these species, the Edwards Aquifer Authority (EAA) and four other local entities created a 15-year Habitat Conservation Plan (HCP). After the HCP was approved in 2013, the EAA requested the input of the National Academies of Sciences, Engineering, and Medicine (the National Academies) to review the plan and its implementation (the statement of task is found in Chapter 1). This report is the third and final product of a three-phase National Academies

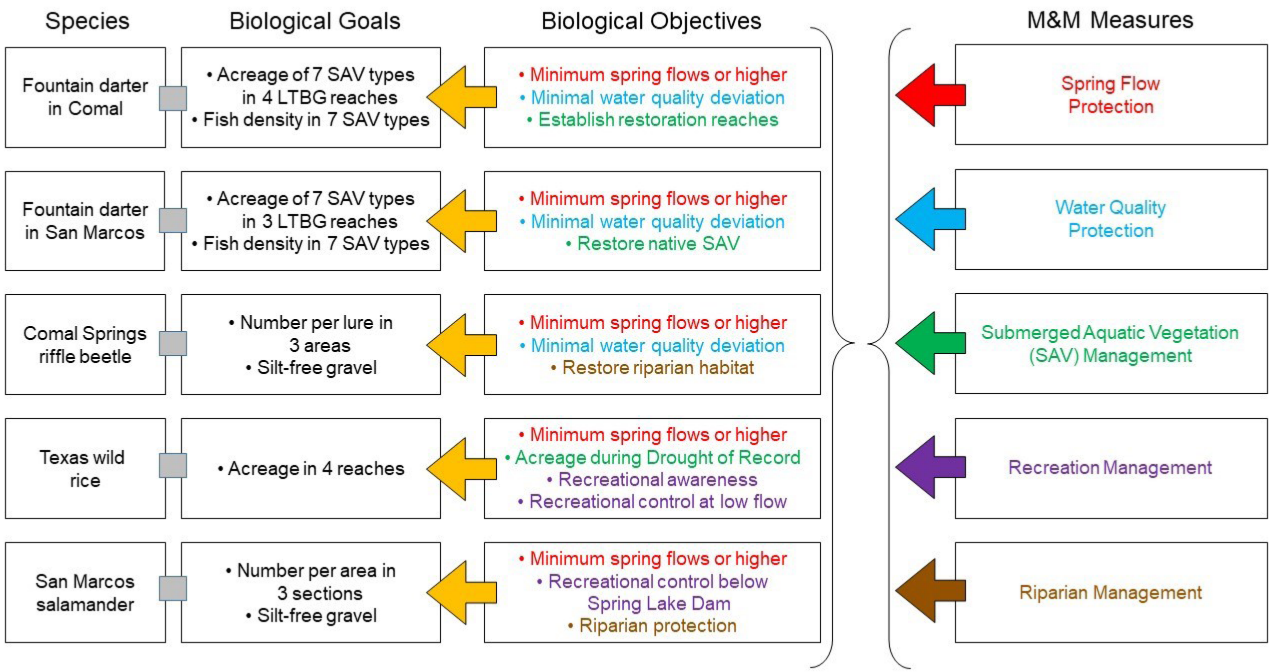



FIGURE S-1 Linkages between the listed species, their biological goals and objectives, and the minimization and mitigation measures. The colors on the far right indicate similar classes of measures: red for measures to maintain minimum flows, blue for measures to maintain good water quality, green for measures to manage SAV, purple for measures to manage recreation, and brown for measures to manage riparian areas. These measures are meant to achieve the objectives shown in the middle column, according to their corresponding color.
NOTE: LTBG = long-term biological goal; SAV = submerged aquatic vegetation.

study to provide advice to the EAA on various scientific aspects of the HCP that will ultimately lead to improved management of the Edwards Aquifer.

The third and final phase of the National Academies' study focuses on the biological goals and objectives found in the HCP for each of the listed species. The first part of the Committee's statement of task asks whether the biological objectives, which have flow, water quality, and habitat components, can meet the biological goals, which are often stated as population measures for the listed species. The second task asks whether the conservation measures in the HCP, also called minimization and mitigation (M&M) measures, can meet the biological objectives.

The biological goals, biological objectives, and M&M measures are shown in Figure S-1 for four of the listed species: fountain darter (shown separately for each system), CSRB, Texas wild rice, and San Marcos salamander. These four species have been identified as sentinel or indicator species that can serve as proxies for the other listed and petitioned species (as discussed in Chapter 2). The gold arrows in Figure S-1 link biological objectives to the biological goals for each species. In particular, these arrows indicate that the spring flow, water quality, and habitat components of the biological objective will work in concert to reach a biological goal (as discussed in greater detail in Chapter 3). The colored arrows in Figure S-1 link M&M measures to certain components of the biological objectives, as indicated by their particular color. For example, the recreation management measures (purple) are intended to help achieve the habitat component of the biological objectives for Texas wild rice and San Marcos salamander. The spring flow protection measures (red) are intended to help achieve the flow component of the biological objectives for all species. Chapter 4 describes the extent to which the five classes of M&M measures can meet their corresponding biological objectives. Chapter 5 considers several overarching issues, including new analyses for the fountain darter and macroinvertebrates and planning for catastrophic events, such as invasive species and floods. Each chapter has conclusions and recommendations that synthesize more technical and more specific statements found within the chapters; the most important conclusions and recommendations are repeated in this summary. This report is intended to be useful to the EAA and other stakeholders of the HCP, other water suppliers dealing with ESA issues, state and federal regulators, and academic and consulting communities.

## THE LISTED SPECIES

For each of the four listed species, Chapter 2 includes a description of the organism's life history and habitat; the biological goals and objectives found in the HCP; and the monitoring, modeling, and applied research done for each organism by the EAA and its contractors. The biological goals for each species tend to reflect the desired population of an organism in the system, such as the number of organisms per unit area, as well as a habitat goal, such as acreage of submerged aquatic vegetation (SAV) or the maintenance of silt-free substrates. The following conclusions and recommendations are made regarding the four sentinel species and their biological goals.

**The habitat-based approach for the biological goals for fountain darter (fountain darter density times submerged aquatic vegetation acreage), rather than an actual measure of fish abundance, is reasonable.** However, the use of the cumulative median density in determining whether the biological goals are being met is problematic because this metric is very insensitive to year-to-year changes in fountain darter densities. It is imperative that the EAA consider a metric that reflects fountain darter density in recent years (e.g., a running mean or median over the most recent four years, or similar) for each vegetation type, and they should monitor it relative to an unchanging baseline (e.g., the cumulative median from the first ten years in the Variable Flow Study dataset, or other appropriate baseline data). The development of the fountain darter population model was very effective in integrating the available information and should be leveraged in the future.

**The long-term biological goals for Texas wild rice (desired acreage in various reaches of the San Marcos River) are appropriate, and this species has benefited from extensive monitoring and decades of study**. The EAA and its partners have taken particular care in mapping of Texas wild rice in the San Marcos River and documenting its restoration since implementation of the HCP. Considerable work done over the last century has revealed the life history and physiology of Texas wild rice, which has expanded our knowledge of the genetic framework of this species and its relatives. There are still some questions about relative competition of Texas wild rice versus other native and nonnative SAV, which could be addressed with mesocosm studies.

**The long-term biological goals for Comal Springs riffle beetle density (number of beetles per cotton lure) should be updated during Phase 2 of the Habitat Conservation Plan to reflect more quantitative and standardized monitoring methods.** The density goals were based on data derived from the Variable Flow Study, which used an unstandardized sampling methodology with no standard operating procedure. It would also be useful to conduct new CSRB studies under the Applied Research Program to better substantiate the biological goal of maintaining silt-free substrate. Beyond the uncertainties that went into deriving these biological goals, uncertainties associated with continued population monitoring and a lack of monitoring of the effects of riparian restoration on maintaining silt-free substrate make it difficult to understand compliance. A reevaluation of how annual median values of beetle abundance are calculated for compliance purposes is needed.

**Both long-term biological goals for the San Marcos salamander—target densities in three reaches and maintenance of silt-free gravel—are reasonable and biologically justifiable.** To meet the abundance goals, the EAA should discontinue calculating cumulative median densities, and instead adopt a metric that reflects salamander density in recent years. Furthermore, the EAA needs to begin monitoring adherence to the goal of maintaining silt-free substrates. Given the considerable spatial variation in salamander abundance data and the inability to accurately estimate salamander numbers, the current sampling method could be supplemented with an additional protocol that uses occupancy estimation. It is also important to eliminate any sampler biases during salamander monitoring. Finally, the San Marcos salamander would benefit from additional studies on its life history, particularly using refugia populations, similar to what has been done for the fountain darter, CSRB, and Texas wild rice and other SAV.

## WILL THE BIOLOGICAL OBJECTIVES MEET THE BIOLOGICAL GOALS?

Chapter 3 addresses whether the biological objectives can meet the biological goals for the listed species. The biological objectives are different for each species, although they have three similar components: flow, water quality, and habitat. For all species in the Comal system the total spring flow discharge can go no lower than 225 cubic feet per second (cfs) as a long-term average, while the minimum flow can go no lower than 30 cfs. For the San Marcos system, the long-term average can go no lower than 140 cfs and the minimum no lower than 45 cfs. The water quality objective is that water quality cannot exceed a 10 percent deviation from historically recorded water quality conditions. The conditions are measured at the spring openings for species that dwell near or in the springs (such as CSRB) and in the river systems for the other species (fountain darter). The habitat objective varies by species and generally refers to restoring the physical aspects of a species' habitat.

The likelihood that the combined effects of the flow objective, the water quality objective, and the habitat objective can achieve the biological goals for each species is given one of four possible ratings: **highly likely**, **likely**, **somewhat likely**, and **unlikely**. The rating **highly likely** corresponds to no concerns about achieving biological goals, **likely** implies the objective is expected to achieve biological goals, **somewhat likely** implies the objective may reach the goals but there are significant concerns, and an **unlikely** rating is given where the objective is not expected to reach biological goals. For each species, the evidence and reasoning that led to the determination are given in Chapter 3, and actions that could be taken to move the determination for a species up to a higher rating are described. The following conclusions and recommendations about the biological objectives meeting the biological goals are made.

**It is *likely* that the biological objectives will meet the biological goals for fountain darter.** Fountain darters are clearly associated with SAV and there have been no recent downward trends in fountain darter densities by habitat type or systemwide changes in SAV coverage, despite the drought and flood years of 2013–2014 and 2015, respectively. The flow objectives are consistent with the habitat suitability modeling for the fountain darter, and adaptive management was used successfully to adjust the long-term biological goals. The rating could be improved by repeating the habitat suitability modeling using more recent data; by further examining fountain darter median densities over time, by vegetative habitat type, and abundance indices both within reaches and systemwide; and by performing a power analysis on fountain darter data to guide the interpretation of false negatives.

**It is *likely* that the biological objectives will meet the biological goals for Texas wild rice.** This conclusion is based on empirical observations of gains in the coverage of Texas wild rice, even in the face of recent floods and droughts; on the compatibility of the flow objective with the habitat suitability modeling for Texas wild rice; and on the adaptive management changes that now include Texas wild rice as fountain darter habitat. As with the fountain darter, monitoring and successful restoration of Texas wild rice to date have led to conclusions offered with relatively high confidence. The rating could be improved by repeating the habitat suitability modeling using more recent data, by creating a defined water quality objective for Texas wild rice, and by adding a habitat objective to continue to remove nonnative SAV.

**It is *somewhat likely* that the biological objectives will meet the biological goals for Comal Springs riffle beetle.** This conclusion is based on the limitations associated with (1) the lack of quantitative monitoring of CSRB populations, (2) determining whether riparian restoration can actually eliminate or significantly reduce siltation at spring openings, and (3) the lack of habitat suitability modeling for CSRB in the monitored reaches. To improve the rating, the following actions should be undertaken. First, it is important to continue to standardize and move toward quantitative sampling of CSRB in order to better understand what the true beetle populations are in the monitored reaches. Second, it is highly recommended that a plan be developed to quantitatively monitor CSRB habitat sedimentation associated with continuing riparian restoration efforts. Finally, if the habitat suitability modeling were repeated in the long-term biological goal reaches, it would increase confidence in the ability of the flow objectives to meet the biological goals.

**It is *somewhat likely* that the biological objectives will meet the biological goals for San Marcos salamander**. A robust monitoring program that could provide evidence of upward trends in abundance is lacking for this species. Much of the current scientific information on the species is based on observations and experiments with captive individuals. There is no water quality objective for the salamander or information on the effects of aquatic gardening. The rating could be improved by creating a water quality objective for San Marcos salamanders, better regulating recreational access to the 50-m reach of the San Marcos River just below Spring Lake Dam, quantifying the outcomes of aquatic gardening and maintenance of silt-free gravel at the salamander study reaches, and augmenting the current sampling protocol with a new method to estimate proportion of area occupied and detection probability of San Marcos salamanders. Controlling access just below Spring Lake Dam and quantifying the maintenance of silt-free gravel should be made high priorities since they could be implemented soon and will help ensure that the stated salamander goals are met.

## WILL THE MINIMIZATION AND MITIGATION MEASURES MEET THE BIOLOGICAL OBJECTIVES?

Chapter 4 addresses whether the M&M measures will meet the biological objectives. Rather than consider the dozens of M&M measures individually, the chapter is organized by *category* of M&M measure, with five major categories being identified: (1) flow protection measures, (2) measures to protect water quality, (3) planting of SAV (including Texas wild rice) and removal of nonnative vegetation, (4) recreation management, and (5) riparian restoration. For each category, the section describes the relevant M&M measures and the extent of their implementation, it shows monitoring data when available, and it summarizes what is known about the effectiveness of M&M measures. Each section concludes with a determination that the suite of measures in that category are **highly effective**, **effective**, **somewhat effective**, **ineffective**, or it **cannot be determined** with available information. Each section also suggests what might be done in the near future to increase the rating for that category. A description of the M&M categories is presented below, followed by the major conclusions and recommendations.

### Flow Protection Measures

The four flow protection measures of the HCP are Critical Period Management Stage V, the San Antonio Water Supply Aquifer Storage and

Recovery, the Voluntary Irrigation Suspension Program Option (VISPO), and the Regional Water Conservation Program. These four flow protection measures are the most expensive elements of the entire HCP and make up 71 percent of the HCP expenses, totaling $12.2 million through 2017. These four measures have been designed to maintain the minimum flows required by the HCP in the Comal and San Marcos systems during the Drought of Record. Given their central importance, a determination of whether these flow protection measures are effective is crucial to evaluating the overall success of the HCP.

**The flow protection measures will be *effective* in meeting the flow component of the biological objectives for all listed species.** Throughout the 2014 drought, during which both VISPO and Critical Period Management Stage IV and V restrictions were triggered, spring flows remained above threshold levels. Recent validation of the MODFLOW model during a drought period suggests that the model conservatively estimates both indicator-well levels and minimum spring flows, particularly at low flows. The model predicted that triggering of the four spring flow protection measures would prevent simulated flows from going below the minimum HCP flow requirements during the Drought of Record. The rating for flow protection measures will move toward highly effective if results of the uncertainty analysis show that the errors are low or if model improvements continue to demonstrate that the model is biased low (i.e., conservatively underestimates well levels and spring flows).

## Water Quality Protection Measures

The M&M measures designed to protect water quality in the Comal and San Marcos systems include stormwater control measures, golf course management, and the management and removal of litter and floating vegetation. These measures are appropriately directed toward watershed activities and not direct action in the rivers, with the exception of removing litter and floating vegetation. Most of the stormwater control measures have not yet been implemented, whereas golf course management and the removal of floating litter and vegetation are ongoing.

The water quality protection measures are meant to achieve the biological objective of maintaining water quality within 10 percent of historical conditions. However, for the CSRB, this objective applies to spring water quality, which is not a target of the M&M measures evaluated in Chapter 4. Hence, this section pertains most directly to the water quality component of the biological objective for the fountain darter.

**The water quality protection measures, focusing primarily on stormwater control, will be *somewhat effective* in meeting the water quality component of the biological objective for the fountain darter in the Comal**

**and San Marcos stream systems.** This assessment is based on whether the measures, many of which have yet to be implemented, are likely to keep water quality from further degrading or to improve water quality. The rating of somewhat effective is based on the difficulty in determining the effectiveness of stormwater control measures as well as the uncertainty in how many projects will be implemented. Of the many suggestions given for how to improve the rating, the most important are tracking project implementation and functioning. There should be formalized project tracking to help with prioritization and success rates.

### Submerged Aquatic Vegetation Restoration

Restoration and maintenance of SAV is a key component of reaching the biological goals for fountain darters because these fish are strongly dependent on a vegetated habitat. There are four M&M measures related to aquatic plants. The first is planting of Texas wild rice, one of the listed species and also recognized as habitat for fountain darters. The other three M&M measures all deal with some aspect of SAV management, including removal of exotic or invasive SAV species and either active planting or maintenance of desired native plants that have been documented as fountain darter habitat. The guiding principles for these three measures are that SAV species known to be able to support the fountain darter at abundances on the order of 5 individuals/$m^2$ or greater are targeted for planting, explicit areal coverages for each SAV type and reach are based on historical records of plant abundance, and nonnative SAV species (even if known to be fountain darter habitat) are actively removed.

**The SAV restoration measures, including the replanting of Texas wild rice, will be *effective* in meeting the habitat component of the biological objective for Texas wild rice and the fountain darter.** These measures have been in place since 2013 and have seen incremental and positive progress in moving the systems from being dominated by nonnative SAV, such as *Hydrilla* and *Hygrophila*, to housing a variety of native SAV species. Removal of nonnative SAV has reduced fountain darter habitat, but this was a known consequence, and future plantings of native SAV combined with expanded areas should compensate. The planting program for Texas wild rice has been particularly successful. The ratings could improve if there were less reliance on intensive planting efforts and less dependence on bryophytes as fountain darter habitat in the Comal system.

### Recreation Management

Human recreational use of the San Marcos and Comal systems has occurred for decades, and continued recreational use of these natural resources is identified as one of the activities covered by the HCP. Some of the recreation-associated M&M measures target habitat protection and water quality issues, such as siltation and turbidity, whereas others are meant to mitigate recreation-associated damage to covered species and are often most important during periods of low flow. The recreational M&M measures include management of recreation in both the Comal and San Marcos systems, the designation of permanent access points and bank stabilization in the San Marcos system, regulation of diving and boating in Spring Lake and Sewell Park, and the creation of State Scientific Areas in the San Marcos system.

**The recreation management measures will be *effective* in meeting the habitat component of the biological objectives for the San Marcos salamander and Texas wild rice.** Establishment of permanent river access points is complete, including terraces and walls to stabilize the riverbank and facilitate river access by the public. Native vegetation has been planted between permanent access points to eliminate public access in these areas. Exclusion areas within the San Marcos River have been actively implemented and maintained when low-flow conditions occur, and substantial outreach efforts have been undertaken to ensure compliance by recreational users. Actions to improve the rating include enrollment of all outfitters in the Certificate of Inclusion program; better control of recreational access to the 50-m stream reach immediately below the Spring Lake spillway; and sustaining, enforcing, and monitoring the suite of actions currently in place.

### Riparian Management

Riparian management measures include restoring native riparian vegetation, stabilizing riparian banks, and preventing shoreline erosion and sedimentation. They are considered critical to the CSRB, but also have relevance for the San Marcos salamander, which shares a goal with the CSRB of maintaining silt-free gravel. Well-executed and monitored riparian management activities may also have positive effects on other listed species, for example, by mediating sediment loading and transport in the San Marcos system and thereby affecting the survival of Texas wild rice or by controlling shading and sedimentation, which can affect growth of native SAV in both systems. Riparian management also supports recreation management by blocking access to portions of the rivers and funneling people to specific access points.

**The Committee is *unable to determine* whether riparian management measures will contribute to achieving the biological objectives of the Comal Springs riffle beetle.** This is due to a lack of quantitative monitoring of the riparian measures to show that they are preventing siltation of adjacent springs, as well as to the substantial maintenance requirements of erosion-control structures. There is the potential for negative effects of nonnative riparian plant removal and replanting activities, such as increased sedimentation of spring substrates. For the other riparian restoration activities (e.g., bank stabilization) in both systems that do not directly affect CSRB habitat, site visits and observations suggest that the riparian restoration measures are effective for reducing erosion and sedimentation that might inhibit the growth of SAV and for supporting recreation management by funneling people to permanent access points.

## OVERARCHING ISSUES

As the EAA plans for implementation of Phase 2 of the HCP and ultimately a renewal of the incidental take permit, it should begin to consider several overarching issues and concerns that may ultimately suggest improvements to the biological goals and objectives and the HCP to better protect the listed species.

### Fountain Darter

Although the habitat-based biological goals for the fountain darter are reasonable because they are easy to measure and quantify (see Chapter 2), the ultimate goal is to ensure that the fountain darter population is sufficiently large to provide a buffer against environmental variation and other possible factors that can affect population abundance. This requires estimates of the total number of fountain darter individuals in each system. Further exploration of the population abundance of the fountain darter, especially with the monitoring data available, could help determine the viable population size. An approach to examining how well population abundances offer a buffer to variation and can lead to recovery of the species is population viability analysis (PVA) modeling. Much of the needed information to construct a PVA model is available because of projects from the Applied Research Program, continued monitoring including responses to extreme events and restoration, and the development of the fountain darter ecological model. As the EAA fine-tunes the biological goals (as was done recently via the nonroutine adaptive management action), there should be some confirmation of the numbers of fountain darters that are dictated by the goals.

### Submerged Aquatic Vegetation

While the existing M&M measures for SAV were found to be effective (see Chapter 4), there are some issues worth considering as work proceeds and certainly in planning for the next phase of the HCP. First, specific areal targets for SAV species may not be necessary. There is a relatively small difference in the number of fountain darters across the species of SAV subject to active management (most commonly managed *Ludwigia, Sagittarria, Cabomba,* and *Potamogeton*), bringing into question the fine-scale, precise management of areal targets that is currently being implemented. Second, it is important to better understand controls on SAV in general, and relative species contributions in particular. If mechanistic understanding is improved, an opportunity may exist to evaluate SAV species targets with the benefit of species-specific habitat requirements that would better inform restoration efforts. Taken together, a relaxation of the targets for species-specific areal SAV coverages and a stronger attempt to identify what factors control SAV success could lead to a lower overall effort without sacrificing the ultimate goal for fountain darters.

### Macroinvertebrate Data Analysis

Macroinvertebrate monitoring is not formally part of the HCP, although a long-term monitoring program has been in place since 2003. Multiple aspects of the macroinvertebrate monitoring program provide great potential to the HCP. First, macroinvertebrate monitoring could serve as a general proxy for the overall ecosystem health of the two spring systems, like that routinely done throughout the United States for wadeable streams. Second, the general monitoring of aquatic invertebrates can provide substantial understanding of, and a powerful database on, the complex natural history of the aquifer. Third, comparisons of the general invertebrate community composition and dynamics could be paired statistically with CSRB population estimates to provide an evaluation of the cotton lure sampling approach. Finally, standard ecological community analyses for macroinvertebrates could ultimately serve as a useful surrogate metric for evaluating the overall HCP, and specifically, the efficacy of the M&M measures related to protecting all troglobitic invertebrates in the Edwards Aquifer.

### Invasive Species, Exotics, and Disease

The HCP addresses control of some nonnative species, particularly those already present in the Comal and San Marcos systems. However, other as yet unknown threats may pose even greater risks than those already present in these systems, including species that introduce diseases or parasites. The introduction and establishment of a high-impact nonnative species could make these systems permanently uninhabitable for one or more covered species, even if all these suitable habitat conditions are maintained. The opportunity to eradicate an introduced species is often limited to a short period before it becomes abundant or widely distributed. Once a population is well established, it can be difficult or impossible to eliminate, rendering reintroduction of covered species from refugia populations infeasible or ineffective. There is an urgent need to develop and implement a plan for early detection of nonnative species and for rapid response to eradicate them before they become established. Given the intensive sampling and monitoring that occur in both spring systems, formalizing an early detection strategy should not be difficult.

### Catastrophic Events

The HCP represents a detailed and comprehensive planning process that is focused on meeting the recognized challenges to the listed species and the Comal and San Marcos spring and river systems. However, there is the potential for catastrophic events that are far outside the historical record and could pose unrecognized challenges to listed species and the systems, and their frequency may increase due to climate change. For example, an event the size of Hurricane Harvey could completely destroy much of the restored SAV in the Comal and San Marcos rivers, directly affecting Texas wild rice and fountain darter habitat, and lead to substantial erosion and sedimentation in areas of the rivers, affecting silt-sensitive species. The MODFLOW model is a potential tool to partially address some of the scenarios that could occur in the future, by evaluating how flow protection measures operate in extreme scenarios. Other models would need to be deployed to evaluate the impacts of extreme events on overland flow, surface water hydrology, sediment transport, and habitat loss. Although not part of the HCP, catastrophic events should begin to receive evaluation for possible inclusion in future take permits and HCP planning.

# 1

# Introduction

South-central Texas is home to one of the most productive karst aquifers in the world—the Edwards Aquifer. The Edwards, which covers an area of approximately 3,600 square miles (Figure 1-1), is the primary source of drinking water for over 2.3 million people in San Antonio and its surrounding communities. In addition, it supplies irrigation water to thousands of farmers and livestock operators in the region, which can account for as much as 30 percent of the total water pumped from the system each year. The Edwards Aquifer has extremely high-yield wells and springs, which respond quickly both to rainfall events and to water withdrawals for irrigation and municipal supply. The region suffers periodically from droughts, with the most recent being from 2010 to 2014. There is a risk that future droughts could reduce flow in the Edwards Aquifer and its major springs (Comal Springs in New Braunfels and San Marcos Springs in San Marcos) to a level low enough to put the aquifer and spring ecosystems in peril.

Comal Springs and San Marcos Springs and their river systems house several plants and animals found nowhere else in the world. Eight of these species are listed as threatened or endangered under the federal Endangered Species Act (ESA): the fountain darter, the San Marcos gambusia (which is presumed extinct), the Texas blind salamander, the San Marcos salamander, the Comal Springs dryopid beetle, the Comal Springs riffle beetle (CSRB), the Peck's Cave amphipod, and Texas wild rice. To protect these species, the Edwards Aquifer Authority (EAA) and four other local entities created a 15-year Habitat Conservation Plan. The EAA is a regional government body tasked with managing domestic, industrial, and agricultural with-

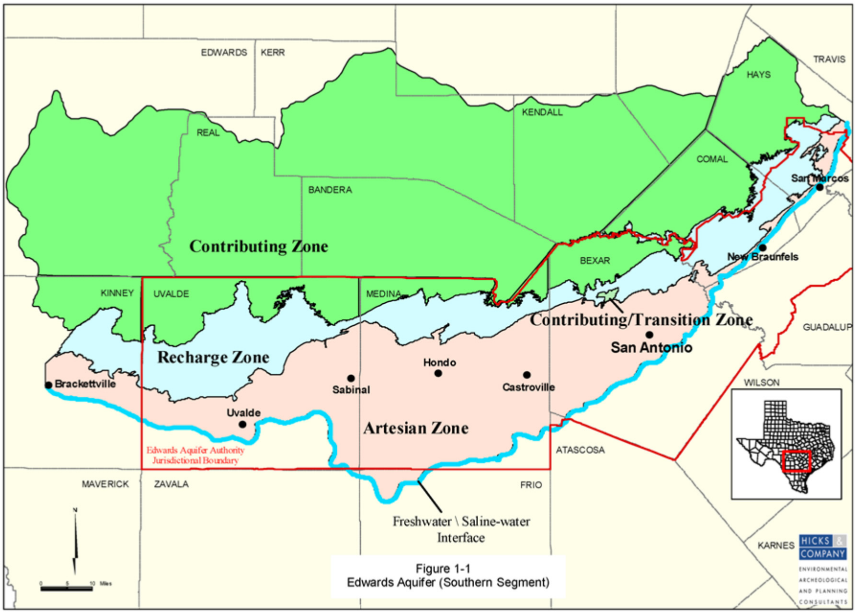



FIGURE 1-1 The Edwards Aquifer, showing the jurisdiction of the Edwards Aquifer Authority. SOURCE: EARIP (2012, Fig. 1-1).

drawals from the Edwards Aquifer while maintaining spring flows at quantities that can support the listed species. The EAA implements the Habitat Conservation Plan (HCP), which the U.S. Fish and Wildlife Service (FWS) finalized and approved in 2013 after a years-long development process. Months later the EAA requested the input of the National Academies of Sciences, Engineering, and Medicine (the National Academies) to review the plan and its implementation. This report is the third and final product of a three-phase National Academies study to provide advice to the EAA on various scientific aspects of the HCP that will ultimately lead to improved management of the Edwards Aquifer. The National Academies' first report (NRC, 2015) provides a comprehensive description of the hydrology of the Edwards Aquifer and its spring systems. The reader is referred to Chapter 1 of that report for in-depth information on these topics. A very cursory summary of Edwards Aquifer hydrology and ecology is presented here, followed by discussion of the HCP.

## HYDROLOGY OF THE EDWARDS AQUIFER

As shown in Figure 1-1, the Edwards Aquifer has contributing and recharge zones to the north, and pumping and artesian wells largely in the south. The *contributing zone* is where rain falls and is directed by streams toward the recharge zone. In the *recharge zone*, precipitation percolates and flows into the groundwater to replenish the aquifer. Groundwater is under high-pressure conditions in the *artesian zone*, such that groundwater flows to the land surface in the form of springs and seeps. At least six springs occur within the artesian zone, including the two largest in Texas, the San Marcos and Comal springs. The Edwards Aquifer is characterized by karst features, such as fractures, caves, and sinkholes, which transport large volumes of groundwater through the system on the order of several days.

Annual precipitation across the region ranges from about 22 inches in the west to over 34 inches in the east. Mean annual precipitation for San Antonio (1934–2013) was approximately 30.38 inches, although this varied annually by as much as 20 inches. Indeed, it is not unusual for the Edwards Aquifer region to experience periods in excess of 40 inches of rain per year separated by droughts. The most significant drought, referred to throughout this report as the Drought of Record, occurred from 1950 to 1956, during which time precipitation was well below the mean annual average for six consecutive years. Evapotranspiration (unhindered vegetative rate) is similarly variable across the region, ranging from more than 60 inches per year in the west to 30 inches per year in the east (Scanlon et al., 2005). Over the long term, precipitation in the region is expected to decrease and evapotranspiration is expected to increase (Loáiciga et al., 2000; Mace and Wade, 2008; Darby, 2010), which, combined with an anticipated population increase, will cause the Edwards Aquifer to be more stressed in the future.

Variations in climate in the Edwards Aquifer region are reflected in the aquifer's water budget. From 1934 to 2016, the median annual recharge was 557,800 ac-ft[1] with a range from 43,700 ac-ft during the Drought of Record to 2,486,000 ac-ft in 1992 (Blanton and Associates, 2018, App. D1). Edwards Aquifer discharge is composed of spring flows and consumptive use through wells. Total annual discharge from six of the most significant springs in the region monitored between 1934 and 2016 varied from 69,800 ac-ft in 1956 to 802,800 ac-ft in 1992, with a median annual discharge of 383,900 ac-ft (Blanton and Associates, 2018, App. D1). Well discharge estimates during the same period ranged from a low of 101,900

[1] An acre-foot (ac-ft) is the amount of water necessary to cover 1 acre of land with 1 foot of water. One acre-foot equals 1,233 cubic meters ($m^3$) of water.

ac-ft in 1934 to a high of 542,400 ac-ft in 1989, with a median annual discharge of 327,800 ac-ft.

## ECOLOGY OF THE EDWARDS AQUIFER

The native species of the springs and river systems flowing from the Edwards Aquifer include a variety of submerged aquatic vegetation (SAV), such as Texas wild rice; several fish, including the fountain darter; amphibians, such as the San Marcos salamander; and a variety of invertebrates. All species in the system depend on adequate spring flow, such that reduced flow in Comal and San Marcos springs has periodically resulted in the intermittent loss of habitat and decreased populations. This loss of habitat from reduced flow is the main reason that eight species have been listed for protection under the federal Endangered Species Act (Table 1-1). Other threats to these species include increased competition and predation from invasive species, direct or indirect habitat destruction or modification by humans (e.g., recreational activities), and other factors, such as high nutrient loading and sedimentation that negatively affect water quality and

TABLE 1-1 Common and scientific names of species proposed for coverage under the Edwards Aquifer Habitat Conservation Plan and their status according to the Endangered Species Act

| Common Name | Scientific Name | ESA Status |
|---|---|---|
| **Fountain darter** | ***Etheostoma fonticola*** | **Endangered** |
| **Comal Springs riffle beetle** | ***Heterelmis comalensis*** | **Endangered** |
| San Marcos gambusia | *Gambusia georgei* | Endangered |
| Comal Springs dryopid beetle | *Stygoparnus comalensis* | Endangered |
| Peck's Cave amphipod | *Stygobromus pecki* | Endangered |
| **Texas wild rice** | ***Zizania texana*** | **Endangered** |
| Texas blind salamander | *Eurycea rathbuni* | Endangered |
| **San Marcos salamander** | ***Eurycea nana*** | **Threatened** |
| Edwards Aquifer diving beetle | *Haideoporus texanus* | Petitioned[a] |
| Comal Springs salamander | *Eurycea* sp. | Petitioned[a] |
| Texas troglobitic water slater | *Lirceolus smithii* | Petitioned[a] |

NOTE: Boldface indicates organisms that are the focus of this report, as discussed further in Chapter 2.
[a]Listed as under review by the U.S. Fish and Wildlife Service (FWS).

habitat (FWS, 1996). It should be noted that these species are covered under the ESA primarily because of their limited range and specialized habitat. As a result, the goals for protecting these species are more about sustaining these populations, rather than rebuilding populations that are in decline.

## HABITAT CONSERVATION PLAN

The ESA, which in this case is enforced by the FWS, protects the listed species from actions that could jeopardize their continued survival. Most relevant to the Edwards Aquifer, the law prohibits the "take" of such species, which the Act defines to mean "harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct." The law also allows certain entities to apply for and receive an incidental take permit, which defines the number of animals that can be "taken" by certain activities (such as groundwater pumping). For an applicant to receive such a permit, it must develop an HCP.

The HCP for the Edwards Aquifer took years to create and involved many parties (see NRC, 2015, for details). It was finally submitted by the EAA to the FWS in 2012, after which an incidental take permit was issued. The permit lasts 15 years, from March 18, 2013, until March 31, 2028. The five official permittees are the EAA, the City of San Antonio acting through the San Antonio Water System, the City of San Marcos, the City of New Braunfels, and Texas State University. All five have responsibilities under the HCP to implement minimization and mitigation (M&M) measures that will protect the listed species and their habitat. The M&M measures that make up the HCP include four spring flow protection measures as well as other measures designed to maintain and restore the habitat of listed species at both Comal and San Marcos springs. A complete list of the measures can be found in NRC (2015) or the HCP itself (EARIP, 2012). The discussion below focuses on the specific measures that are evaluated in this report for their ability to meet biological goals and objectives for the listed species.

The four spring flow protection measures were designed to provide adequate water during drought and include (1) critical period management, (2) regional water conservation, (3) a voluntary irrigation suspension program, and (4) aquifer storage and recovery. Critical period management refers to reductions in permitted discharges when the spring flow at Comal and San Marcos Springs, or water levels at reference wells J-17 and J-27, fall below certain levels. To offset the risks to listed species under these conditions, the HCP instituted a fifth stage, which would mandate reductions in pumping of 44 percent. The Regional Water Conservation Program builds upon the demand management already being conducted by the City of San Antonio. It is envisioned that new municipal conservation activities can save approximately 10,000 ac-ft/yr (12.33 million $m^3$/yr). The

Voluntary Irrigation Suspension Program Option targets the 30 percent of annual Edwards Aquifer pumping that is withdrawn for irrigation. It relies on permitted irrigators relinquishing their pumping rights when well levels drop below certain triggers; it is intended to conserve another 40,000 ac-ft/yr (49.32 million $m^3$/yr). Finally, the San Antonio Water System runs an aquifer storage and recovery operation in the Carrizo Aquifer that is predicted to make the greatest contribution to overall Edwards Aquifer water savings (as much as 100,000 ac-ft/yr or 123.3 million $m^3$/yr).

Beyond the spring flow protection measures there are a variety of M&M measures designed to maintain and restore the habitat of listed species at both Comal and San Marcos springs. This report evaluates measures to preserve water quality, restore submerged aquatic vegetation, manage recreational activities, and restore riparian areas. This report also considers the refugia created to house populations of the listed species.

## THE EAA-REQUESTED STUDY

In late 2013, the EAA requested the involvement of the National Academies to advise on the many different scientific initiatives under way to support the HCP. An expert committee of the National Academies was asked to focus on the adequacy of the scientific information being used to, for example: (1) set biological goals and objectives, (2) determine what M&M measures to use and their effectiveness, and (3) make decisions about the transition from Phase 1 to Phase 2 of the HCP. The study was conducted in three phases from 2014 to 2018 and produced three main reports and one interim report.

Phase 1 of the National Academies study addressed five programs within the HCP: hydrologic modeling, ecological modeling, the biological and water quality monitoring programs, and the Applied Research Program. The resulting report (NRC, 2015) was released in late February 2015. In general, the report was complimentary of the efforts of the EAA and its partners in implementing the HCP and these five programs in particular, while identifying areas that could be improved upon. Many of the report's recommendations are being implemented, including moving to a single platform for hydrologic modeling, performing uncertainty analysis on the hydrologic model, developing a conceptual model for ecology in both spring systems, devoting new resources to better understanding the CSRB, creating a data management system, and performing statistical analysis of their biomonitoring data.

Phase 2 of the study and the second report (NASEM, 2017) took a much more in-depth look at the ecological model being developed by the EAA and made many recommendations for improving the model. This information was provided to the EAA at an early time point (in the form of an interim report—NASEM, 2016) to allow its incorporation into model development. The second report also discussed scenarios that could be run in the hydrologic model, particularly the testing of the model against data that were not used in the model calibration—a recommendation that was subsequently followed up on by the EAA. The water quality and biological monitoring programs were again reviewed in the second report, as were the studies that make up the Applied Research Program. Finally, the Committee reviewed implementation of several M&M measures, including the flow protection measures, removal of nonnative SAV and replanting of SAV and Texas wild rice, sediment management, and dissolved oxygen management in Landa Lake. Partly as a result of the Committee's recommendations, sediment removal in the San Marcos system and dissolved oxygen management in Landa Lake were discontinued.

After the release of each of the two main National Academies reports, the EAA went through a lengthy process to determine how to implement the recommendations of the Committee. Formal response documents, called implementation reports (EAA, 2015, 2017), were created that responded to every recommendation. Although the first implementation report was read and utilized by the Committee during Phase 2 of its study, the second has not been comprehensively reviewed by the Committee because it does not pertain to the tasks of Phase 3.

## Phase 3 of the National Academies' Study

The third and final phase of the National Academies' study focuses on the biological goals and objectives found in the HCP for each of the listed species (Box 1-1). The first task asks whether the biological objectives, which have flow, water quality, and habitat components, can meet the biological goals, which are often stated as population measures for the listed species. The second task asks whether the M&M measures can meet the biological objectives. For consistency, this report adheres to the terminology used in the HCP of "biological goals" and "biological objectives." In other circles, biological goals are more commonly referred to as "conservation goals." The biological goals tend to focus on measures of organism abundance, while the biological objectives deal with the flow, water quality, and habitat conditions necessary to maintain organism abundance.

With respect to evaluating whether the M&M measures can meet the biological objectives, the Committee considered a subset of the 39 M&M measures listed in the HCP, for several reasons. First, many of the M&M measures are not truly conservation measures but are in fact programs (like the monitoring programs) run by the EAA and were already reviewed by the National Academies. Second, some M&M measures listed in the HCP are not directly tied to the achievement of a biological objective, nor were

**BOX 1-1**
**Review of the Edwards Aquifer**
**Habitat Conservation Program—Phase 3**
**Statement of Task**

An ad hoc committee of the National Academies of Sciences, Engineering, and Medicine (NASEM) will conduct a study from 2014 to 2018 and issue three reports that review the many different scientific initiatives under way to support the Edwards Aquifer Habitat Conservation Plan (HCP). The Committee will focus on the adequacy of information to reliably inform assessments of the HCP's scientific initiatives, ensuring that they are based on the best available science. In early 2015 the Committee issued its first report, which focused on hydrologic modeling, ecological modeling, water quality monitoring and biomonitoring, and the Applied Research Program. The Committee wrote an interim report on the ecological model in June 2016, and a second full report on the entire program in December 2016. The third and final report will focus on the relationships among proposed conservation measures (including flow protection measures and habitat restoration), biological objectives (such as water quality criteria, habitat condition, and specified spring flow rates), and biological goals (such as maintaining populations of the Covered Species). (The Biological Goals, which were agreed upon by the U.S. Fish and Wildlife Service, are considered fixed for the purposes of this study.) In particular, the Committee will determine, for each Covered Species in the EAHCP:

1. Whether the biological objectives in the EAHCP are highly likely, somewhat likely, or unlikely to achieve the related biological goals. If "highly likely," is the full complement of biological objectives necessary to meet the biological goals? If the biological objectives are "unlikely" to achieve the biological goals, recommend how the amounts/types of habitat and water quality objectives could be amended to achieve the biological goals.
2. Whether the conservation measures in the EAHCP are adequate to meet the biological objectives. Is the full suite of conservation measures necessary to meet the biological objectives? Additionally, if the conservation measures are not adequate, would the presumptive Phase 2 conservation measure or simple manipulation of a Phase 1 conservation measure achieve the biological objectives? If neither the Phase 1 conservation measures nor the presumptive Phase 2 conservation measure are likely to achieve the biological objectives, the Committee will explain the extent to which the objectives are not likely to be achieved, and why.

they highlighted by the EAA as important for consideration in this final report. As a consequence, this report evaluated five major categories of M&M measures, comprising about 75 percent of those listed in the HCP. These categories, shown as gray rows in Table 1-2, are (1) spring flow pro-

TABLE 1-2 Minimization and Mitigation (M&M) Measures Considered in this Report

| M&M Measure | Habitat Conservation Plan Section(s) |
|---|---|
| *Spring Flow Protection* | |
| Voluntary Irrigation Suspension Program Option | 5.1.2 |
| Regional Water Conservation Program | 5.1.3 |
| Critical period management | 5.1.4 |
| Aquifer storage and recovery | 5.5.1 |
| *Water Quality Protection* | |
| Decaying vegetation removal program | 5.2.4 |
| Management of floating vegetation mats and litter removal | 5.3.3 and 5.4.3 |
| Low-impact development/best management practices | 5.7.3 |
| Best management practices for stormwater control | 5.7.6 |
| *SAV Management* | |
| Landa Lake and Comal River aquatic vegetation restoration and maintenance | 5.2.2 |
| Old Channel Environmental Restoration and Protection Area | 5.2.2.1 |
| Texas wild rice enhancement and restoration | 5.3.1, 5.4.1 |
| SAV restoration (nonnative removal and native reestablishment)/maintenance | 5.3.8, 5.4.3, 5.4.12 |
| *Recreation Management* | |
| Recreation control in key areas | 5.3.2, 5.4.2 |
| Bank stabilization/permanent access points | 5.3.7 |
| Management of public recreational use | 5.3.2.1 |
| Boating in Spring Lake and Sewell Park | 5.3.10 |
| Diving classes in Spring Lake | 5.4.7 |
| Creation of scientific areas | 5.6 |
| *Riparian Management* | |
| Riparian improvements and sediment removal specific to the Comal Springs riffle beetle | 5.2.8 |
| Bank stabilization/permanent access points | 5.3.7 |
| Restoration of riparian zone with native vegetation | 5.7.1 |

tection, (2) water quality protection, (3) SAV management, (4) recreation management, and (5) riparian management.

The **spring flow protection** measures that are evaluated include the Voluntary Irrigation Suspension Program Option, the Regional Water Conservation Program, the aquifer storage and recovery program of the San Antonio Water System, and emergency withdrawal reductions during Stage V Critical Period Management. Each of these four measures is intended to contribute, in a cumulative fashion, to maintaining an adequate level of continuous spring flow during a repeat of the Drought of Record conditions

(EARIP, 2012). The **water quality protection** measures include stormwater best management practices, water quality protection plans, management of golf course diversions, and removal of floating leaf litter. The **SAV management** measures are designed to restore native vegetation, including Texas wild rice enhancement and restoration in the San Marcos system, nonnative SAV removal in both systems, and SAV restoration and maintenance in both the Comal and San Marcos systems. **Recreation management** includes the creation of permanent access points, State Scientific Areas, and regulation of boating on and diving in Spring Lake. Finally, **riparian management** includes replacing invasive riparian plants with native vegetation in both systems.

Figure 1-2 shows the biological goals, biological objectives, and M&M measures for four of the listed species considered in this report: fountain darter (shown separately for each system), CSRB, Texas wild rice, and San Marcos salamander. These four species have been identified as sentinel or indicator species that can serve as proxies for the other listed and petitioned species (see Chapter 2).

Figure 1-2 requires explanation in order for the reader to understand the report's organization. First, the middle columns show the biological goals and objectives for the four species and are paraphrased from the HCP. Details (such as the exact densities of species and the areas in which these numbers must be achieved) can be found in Chapter 2. As mentioned earlier, the column on biological objectives has three components per species: flow, habitat, and water quality, which are indicated with colored text. Red text indicates the flow component, blue text the water quality component, and green text the habitat component of the biological objectives. Note that Texas wild rice and the San Marcos salamander were not assigned a water quality component (and hence have no blue text). Also, some of the habitat components of the biological objectives are worded redundantly with an M&M measure; those that overlap with a recreation management measure appear in purple text while those that overlap with a riparian management measure appear in brown text. The far-right column shows the M&M measures, which are color coded to assist the reader in linking M&M measures to certain components of the biological objectives. Note that Figure 1-2 shows only the five broad categories of M&M measures, not the individual measures listed in Table 1-2.

The gold arrows in Figure 1-2 link biological objectives to the biological goals for each species. (Note that the biological objectives and goals for fountain darters are slightly different for the two systems.) In particular, these arrows indicate that the spring flow, water quality, and habitat components of the biological objective are intended to work in concert to reach a biological goal. **The Committee's first task was to say whether the biological objectives will meet the biological goals (i.e., whether the gold**

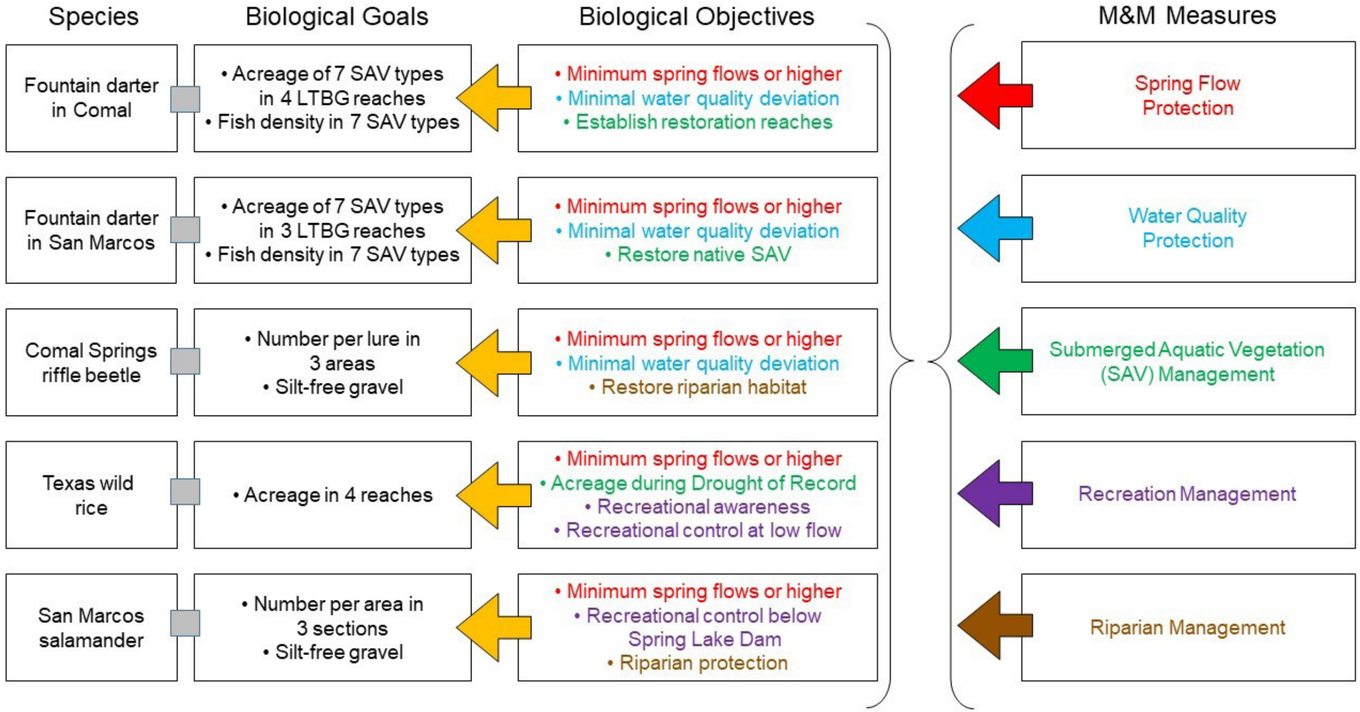



FIGURE 1-2 Linkages between the listed species, their biological goals, biological objectives, and the M&M measures.
NOTE: LTBG = long-term biological goal; SAV = submerged aquatic vegetation.

**arrows should be labeled as "highly likely," "likely," "somewhat likely," or "unlikely").**

The other colored arrows in Figure 1-2 link M&M measures to certain components of the biological objectives, as indicated by their particular color. For example, the recreation management measures are intended to help achieve the habitat component of the biological objectives for Texas wild rice and the San Marcos salamander. The spring flow protection measures are intended to help achieve the flow component of the biological objectives for all species. **The second task of the Committee was to say whether the M&M measures can achieve the biological objectives (i.e., whether the red, blue, green, purple, and brown arrows should be labeled as "highly effective," "effective," "somewhat effective," "ineffective," or "cannot be determined").**

Chapter 2 discusses the four primary listed species in greater detail, including information about their life history, their biological goals and objectives, and how they are monitored in both systems. Chapter 3 of this report addresses whether the biological objectives can reach the biological goals. This is done for each of the four species shown in Figure 1-2. Chapter 4 considers whether the groups of M&M measures can meet the various biological objectives. Chapter 5 considers several overarching issues, including new analyses for fountain darters and macroinvertebrates and planning for catastrophic events, such as invasive species and floods. Each chapter ends with conclusions and recommendations that synthesize more technical and specific statements found within the body of each chapter. The most important conclusions and recommendations are repeated in the report summary. It should be noted that substantial information provided in the first National Academies report, such as the descriptions of each program, definitions of terms, and rationale for previous recommendations, is not repeated in this report. The reader is referred to NRC (2015) and NASEM (2016, 2017) for such details.

It is also important to recognize what this report does not include. First, in its efforts to evaluate the likelihood of the biological objectives meeting the biological goals, and of the M&M measures meeting the biological objectives, the Committee identified actions that might *enhance* the likelihood. However, it did not seek to identify responses to the hypothetical situation of the current measures failing to meet either biological objectives or goals. Second, the Committee did not evaluate the influence of external factors, such as population growth and associated increases in water demand on the ability of the M&M measures to meet the objectives. Changes in water demand are handled outside of the HCP by the process through which the EAA distributes permits to water users. Third, this report does not repeat all of the important issues, conclusions, and recommendations from the Committee's first three reports (NRC, 2015; NASEM, 2016, 2017). For example, the ecological model is not revisited here, nor is the issue of the representativeness of sampling sites.

The HCP defined biological goals and biological objectives for each of the listed species, and this necessarily placed constraints on the Committee. For example, the biological goals were considered immovable for the purposes of this study, and so Chapter 2 does not critique the specific numeric goals. The flow objectives specify only minimum flow requirements for the listed species because a major goal of the HCP is to protect those species during a recurrence of the Drought of Record. As a result, the report does not consider the full extent of the flow regime on the listed species, although a discussion of extreme flows and their impacts is found in Chapter 5.

Finally, the HCP was written to protect the listed species and their habitat during the 15-year window of the incidental take permit, during which the effects of climate change were not considered (by design). Hence, this report does not consider how climate change may affect the ratings that the Committee assigned to the biological objectives and M&M measures of the HCP. Nonetheless, the Committee recognizes the potentially important role of climate change in the future success of any efforts to protect the listed species, and it explicitly addressed this issue in its first report (NRC, 2015). Climate change is also briefly revisited in Chapter 5.

## REFERENCES

Blanton and Associates, Inc. 2018. Edwards Aquifer Habitat Conservation Plan 2017 Annual Report. Prepared for the U.S. Fish & Wildlife Service. March 26. http://www.eahcp.org/files/admin-records/NEPA-and-HCP/EAHCPAnnualReport2017v3_20180313_Redlined_from_Blanton.pdf.

Darby, E. B. 2010. The role of ESA in an atmosphere of climate change regulations. CLE International Conference: Endangered Species Act: Challenges, Tools, and Opportunities for Compliance, June 10-11, 2010, Austin, TX. http://www.eahcp.org/documents/2010_Darby_EndangeredSpeciesAct.pdf.

EAA (Edwards Aquifer Authority). 2015. National Academy of Sciences Review of the Edwards Aquifer Habitat Conservation Plan: Report 1 Implementation Plan. August 20.

EAA. 2017. Edwards Aquifer Habitat Conservation Plan: Report 2 Implementation Plan. July 31. http://www.eahcp.org/files/uploads/Final_Report_2_Implementation_Plan_2017_07_31.pdf.

EARIP (Edwards Aquifer Recovery Implementation Program). 2012. Habitat Conservation Plan. http://www.eahcp.org/files/uploads/Final%20HCP%20November%202012.pdf.

FWS (U.S. Fish and Wildlife Service). 1996. San Marcos and Comal Springs and Associated Aquatic Ecosystems (Revised) Recovery Plan. Albuquerque, NM: FWS. https://www.cabi.org/isc/FullTextPDF/2011/20117202434.pdf.

Loáiciga, H. A., D. R. Maidment, and J. B. Valdes. 2000. Climate-change impacts in a regional karst aquifer, Texas, USA. Journal of Hydrology 227:173-194.

Mace, R. E., and S. C. Wade. 2008. In hot water? How climate change may (or may not) affect the groundwater resources of Texas. Transactions of the Gulf Coast Association of Geological Societies 58:655-668.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2016. Evaluation of the Predictive Ecological Model for the Edwards Aquifer Habitat Conservation Plan: An Interim Report as Part of Phase 2. Washington, DC: The National Academies Press.

NASEM. 2017. Review of the Edwards Aquifer Habitat Conservation Plan: Report 2. Washington DC: The National Academies Press.

NRC (National Research Council). 2015. Review of the Edwards Aquifer Habitat Conservation Plan: Report 1. Washington DC: The National Academies Press.

Scanlon, B., K. Keese, N. Bonal, N. Deeds, V. Kelley, and M. Litvak. 2005. Evapotranspiration Estimates with Emphasis on Groundwater Evapotranspiration in Texas. Prepared for the Texas Water Development Board. December. http://www.twdb.texas.gov/groundwater/docs/BEG_ET.pdf.

# 2

# The Listed Species

Four of the listed species are discussed in detail in this chapter: the fountain darter, Texas wild rice, the Comal Springs riffle beetle (CSRB), and the San Marcos salamander. Each discussion includes a description of the organism's life history and habitat. In addition, the biological goals and objectives found in the Habitat Conservation Plan (HCP) for each organism are given. The biological goals tend to reflect the desired population of an organism in the system, such as the number of organisms per unit area. The biological objectives usually have three components: flow requirements, generic water quality criteria, and qualitative characteristics of the organism's desired habitat. The sections below also discuss the monitoring done for each organism by the Edwards Aquifer Authority (EAA) and its contractors.

Although there are eight listed species (seven that are endangered including one presumed extinct and one that is threatened, plus three petitioned species (see Table 1-1), this report focuses on the four species listed above for two primary reasons. First, the HCP identifies three indicator species: the fountain darter, Texas wild rice, and the CSRB. The indicator species are intended to represent the other listed species: the Comal Springs dryopid beetle, the Peck's Cave amphipod, the Edwards Aquifer diving beetle, the Texas troglobitic water slater, the Comal Springs salamander, the San Marcos salamander, the Texas blind salamander, and the San Marcos gambusia (EARIP, 2012, p. 4-38). That is, in accordance with the 2008 U.S. Fish and Wildlife (FWS) Strategic Habitat Conservation Handbook (FWS, 2008), the plan assumes that the conservation measures developed for these three "indicator" (sometimes referred to as "sentinel") species will be sufficient to protect all of the listed species.[1] The use of indicator species is felt to be an important way of containing the costs of implementing conservation measures, as well as the costs and time-consuming efforts associated with processing individual incidental take permits under the Endangered Species Act (FWS, 2013). However, because certain conservation measures found in the HCP are specific to the non-sentinel San Marcos salamander, the Committee includes this species in the detailed discussion below. Second, there is considerable overlap and redundancy among the goals and objectives for the eight species, with much less specificity provided for the species that are not discussed in detail. By focusing on the four species in Figure 1-2, the Committee was able to provide some rational bounds to its analysis. As will be evident from this chapter, much more is known about the life histories and habitat requirements of the indicator species compared to the others.

## FOUNTAIN DARTER

### Description and Life History

The life history of the fountain darter has been described in many documents (Schenck and Whiteside, 1977; Brandt et al., 1993; Labay and

[1] The use of the CSRB as an indicator of the other ESA-listed invertebrates is problematic because of a lack of information on the beetle's spatial distribution, range of potential habitats, and natural history. As pointed out in NRC (2015), "The degree to which the CSRB is a reliable indicator is presently not well understood nor has it been objectively tested." Recent Applied Research projects strive to fill these knowledge gaps.

Brandt, 1994; McDonald et al., 2007; Alexander and Phillips, 2012; Becker et al., 2012; Dammeyer et al., 2013). Fountain darters live about one to two years, with adults reaching 1-2 inches in length. They have an affinity for the bottom (sand and gravel substrates) and relatively still waters and preferentially inhabit vegetation. Spawning occurs year-round with peaks in the spring and lows in the late summer and fall. Temperatures of about 22–23°C are favorable, and reproduction stops when water is warmer than 26°C. Females are batch spawners and deposit eggs in vegetation that are then fertilized with no further parental care. The young are restricted to the stream bottom until they can swim through currents. Adults show limited daily movement and are visual feeders that eat copepods, amphipods, and insect larvae using a stationary foraging style. Fountain darters are vulnerable to infection by the gill trematode (*Centrocestus formosanus*).

There are four fundamental processes that dictate how individual fish progress through the life cycle. The four interrelated processes are growth (which determines development), mortality, reproduction, and movement. The HCP goals are based on abundance and densities of fountain darters, and so the processes of growth and movement are only important if they affect mortality or reproduction. Otherwise, growth and movement result in the same number of individuals that are just smaller or larger or located in a different place. Available data suggest that fountain darters have a limited spatial range. Dammeyer et al. (2013) estimated a maximum displacement of 95 meters within 26 days. Such high site fidelity typically increases the risk of sudden population declines. Localized problems with water quantity and quality and with habitat can create slow and delayed movement responses of individuals and also slow colonization of new habitat if connectivity is not considered. Given the small domain of both systems, this issue is likely of secondary importance.

The population dynamics of fountain darters are based on their densities and habitat availability in the long-term biological goal (LTBG) reaches. However, the domain of interest is the entire system because that constitutes the biological unit used for listing and recovery assessment. The first National Academies report (NRC, 2015) discussed what role the LTBG reaches play in the interpretation of fountain darter population dynamics. A key question is: Can the LTBG reaches be interpreted as representative of other, unmonitored reaches and therefore be scaled up to system-level population abundances? Or do the LTBG reaches effectively constitute the major habitat available and therefore the number of fountain darters in the LTBG reaches can be viewed as the population abundance for the entire system? It is the latter; EAA treats the LTBG reaches as constituting the entire population of fountain darters when determining population abundance goals in each of the systems.

Historically, the geographic extent of fountain darters in the San Marcos system was from Spring Lake to about 0.5 mi (0.8 km) past the confluence with the Blanco River, and in the Comal system from Landa Lake to the confluence with the Guadalupe River. Presently, fountain darters reside in the upper Comal River, including Landa Lake, and the San Marcos River between Spring Lake and the City of San Marcos wastewater treatment plant outfall. The HCP refers to proportional expansion as a way to scale habitat restoration from the LTBG reaches to the system; however, proportional expansion is rather vaguely described in the HCP. Recently, the EAA has done what it considers a version of proportional expansion by adding new restoration reaches to the LTBG reaches because the biological goals were not obtainable by considering only the LTBG reaches. There is now an assumption that the LTBG and restoration reaches are considered the entire system when computing fountain darter population abundance.

## Biological Goals and Objectives

The biological goals for fountain darters are stated as a specific areal coverage by submerged aquatic vegetation (SAV) type ($m^2$) and minimum densities of fountain darter per square meter of each SAV type (Table 2-1). SAV coverage is measured in the LTBG and restoration reaches, while fountain darter density is measured only in the LTBG reaches. Maps of the LTBG and restoration reaches are shown in Figure 2-1. When the SAV areal coverages and fountain darter densities are multiplied, these goals result in the LTBG and restoration reaches supporting about 176,000 fountain darter juveniles and adults in the Comal system and 35,000 in the San Marcos system. This method of determining population abundance is discussed further in Chapter 5.

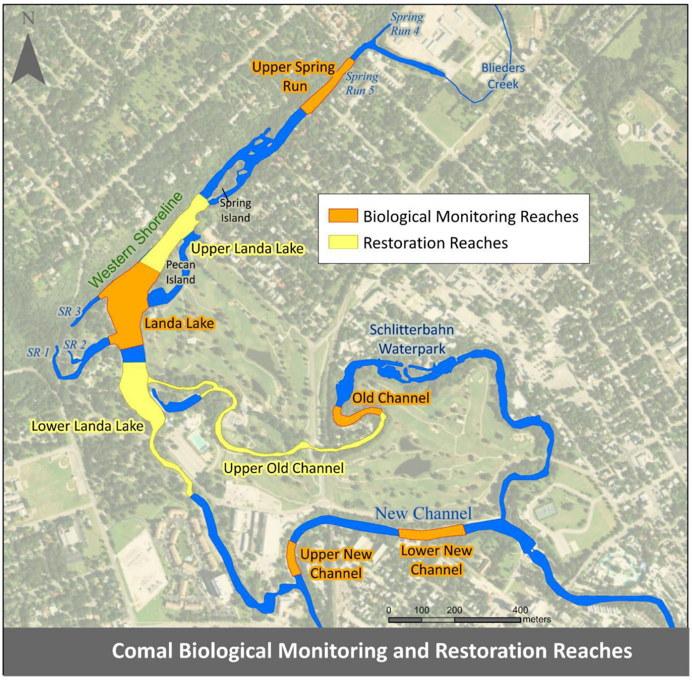
The goals in Table 2-1 were derived primarily from data collected as part of the EAA Variable Flow Study (BIO-WEST, 2011a,b). Areal coverages of the major habitat types were roughly set to the maximum values observed during the ten-year study for each reach, with consideration given to whether the maximum coverages observed for each habitat type in each reach, some of which occurred in different years, could possibly occur concurrently within the reaches. According to the HCP (EARIP, 2012, pp. 4-2 and 4-24), fountain darter densities by SAV type were also estimated from the same Variable Flow Study as the median densities across samples, years, and reaches within each system. However, the Committee notes that in its examination of the drop-net data for fountain darters, there were few to no fountain darter densities measured for *Hydrocotyle, Ludwigia, Sagittaria,* and Texas wild rice in the San Marcos system and for *Potamogeton* in both systems. For these SAV types, which were added to the goals by amendment of the HCP in 2016, fountain darter densities were estimated based on more recent observations (BIO-WEST and Watershed Systems Group, 2016).

TABLE 2-1 Long-Term Biological Goals for Fountain Darters in the Comal and San Marcos Systems

| Comal Springs Fountain Darter Habitat, Submerged Aquatic Vegetation, $m^2$ | | | | | | |
|---|---|---|---|---|---|---|
| Study Reach | *Potamogeton* | *Ludwigia* | *Cabomba* | *Sagittaria* | *Bryophytes* | *Vallisneria* |
| Upper Spring Run | | 25 | 25 | 850 | 1,750 | |
| Landa Lake | 25 | 900 | 500 | 2,250 | 3,950 | 12,500 |
| Old Channel | | 425 | 180 | 450 | 550 | |
| New Channel | | 100 | 2,500 | | 150 | |
| TOTAL | 25 | 1,450 | 3,205 | 3,550 | 6,400 | 12,500 |
| **Comal Springs Fountain Darter Median Density, number/$m^2$** | | | | | | |
| | *Potamogeton* | *Ludwigia* | *Cabomba* | *Sagittaria* | *Bryophytes* | *Vallisneria* |
| | 3.3 | 7 | 7 | 1 | 20 | 1 |
| **San Marcos Springs Fountain Darter Habitat, Submerged Aquatic Vegetation, $m^2$** | | | | | | |
| Study Reach | *Potamogeton* | *Ludwigia* | *Cabomba* | *Sagittaria* | *Hydrocotyle* | *Zizania* |
| Spring Lake Dam | 200 | 100 | 50 | 200 | 50 | 700 |
| City Park | 1,450 | 150 | 90 | 300 | 10 | 1,750 |
| I-35 | 250 | 50 | 50 | 150 | 50 | 600 |
| TOTAL | 1,900 | 300 | 190 | 650 | 110 | 3,050 |
| **San Marcos Springs Fountain Darter Median Density, number/$m^2$** | | | | | | |
| | *Potamogeton* | *Ludwigia* | *Cabomba* | *Sagittaria* | *Hydrocotyle* | *Zizania* |
| | 5 | 7 | 7 | 1 | 4 | 5 |

SOURCE: BIO-WEST and Watershed Systems Group (2016).

A




B

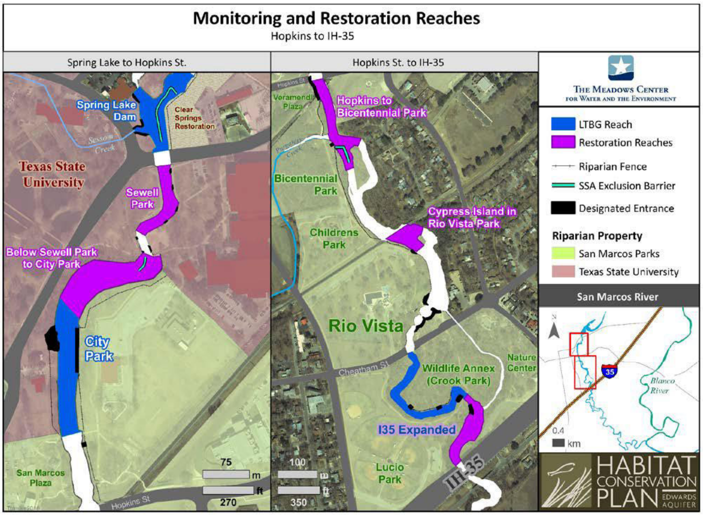



FIGURE 2-1 Long-term biological goal and restoration reaches for the fountain darter in the Comal (A) and San Marcos (B) systems. SOURCE: Furl (2017).

Compliance with the biological goals is evaluated using extensive mapping of SAV coverages in the LTBG and restoration reaches and cumulative median fountain darter densities by SAV type. The use of a cumulative median density is very insensitive to year-to-year changes in fountain darter densities (Box 2-1). Indeed, there is no theoretical or statistical basis for using the cumulative median, and its insensitivity to change can create risks to understanding the status of the fountain darter.

The biological objectives for fountain darters have three components: habitat, flow, and water quality. The habitat objective is to restore native vegetation. Fountain darters are associated with SAV, with different

**BOX 2-1**
**Calculation of Median Densities to Track Achievement of Biological Goals**

The method used to compute median fountain darter densities to show compliance with the biological goals is insensitive to variation in observed densities, which is problematic. Presently, the Edwards Aquifer Authority (EAA) adds each year's data to the previous years' densities to compute a new median. Computationally, it is difficult to change a median value very much when it has inertia in the form of contributions from earlier years. Indeed, the median is used in statistical analysis because of its stability and resistance to sharp changes caused by a few data points. It is possible that as habitat quality decreases, only extreme decreases in fountain darter densities would be detectable in the multiyear median densities. For example, an analysis of the EAA drop-net data showed that for some vegetation types (e.g., bryophytes and *Vallisneria* in the Comal system), one could replace the most recent two years of observed fountain darter densities with zero values, and the cumulative median fish density value would remain virtually unchanged. EAA staff have indicated that if they were to see any marked declines in observed fountain darter densities they would notify the U.S. Fish and Wildlife Service. Nevertheless, it would make more sense if the metric used to officially monitor fountain darter status was based on only recent years. One such option would be to calculate a metric reflecting fountain darter density in recent years (e.g., a running mean or median over the most recent four years, or similar) for each vegetation type and monitor it relative to an unchanging baseline (e.g., the cumulative median from the first ten years in the Variable Flow Study dataset, or other appropriate baseline data).

The Committee recommends, as the HCP enters into Phase 2, an evaluation of how compliance with fountain darter density goals is conducted. Analyses of the historical data and new data as they arrive should explore the behavior of various ways to compute median fountain darter densities that are responsive to year-specific variation. This issue of how to compute median densities also applies to similar calculations done for the San Marcos salamander and the Comal Springs riffle beetle.

densities found among the vegetation taxa, as shown in Figures 2-2 and 2-3. Figure 2-2 is based on the drop-net sampling and uses the estimated coverage of the dominant vegetation type in each sample. It shows that greater coverage of SAV in the drop-net sample allows for higher densities of fountain darters but does not guarantee higher densities. Figure 2-3 uses the same drop-net data and shows that fountain darter densities are generally higher in some SAV types over others, with a strong preference for bryophytes and filamentous algae. However, the error bars (interquartile range) are relatively wide, suggesting that fountain darter densities vary greatly within many of the SAV types, and thus the densities overlap among many of the SAV types.

The flow component of the biological objectives is to maintain a long-term average total Comal discharge above 225 cubic feet per second (cfs) with a minimum of 30 cfs that is not to exceed six months in duration, followed by at least 80 cfs for three months. For fountain darters in the San Marcos system, the flow objective is to maintain a long-term average

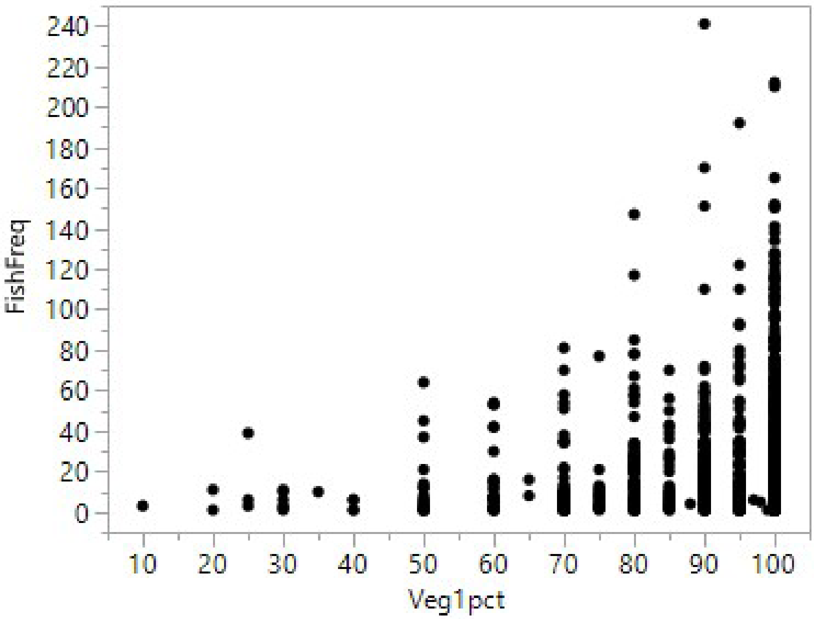



FIGURE 2-2 Fish frequency (number/2-m$^2$ trap) related to percent cover of submerged aquatic vegetation. SOURCE: Committee manipulation of Edwards Aquifer Authority data.

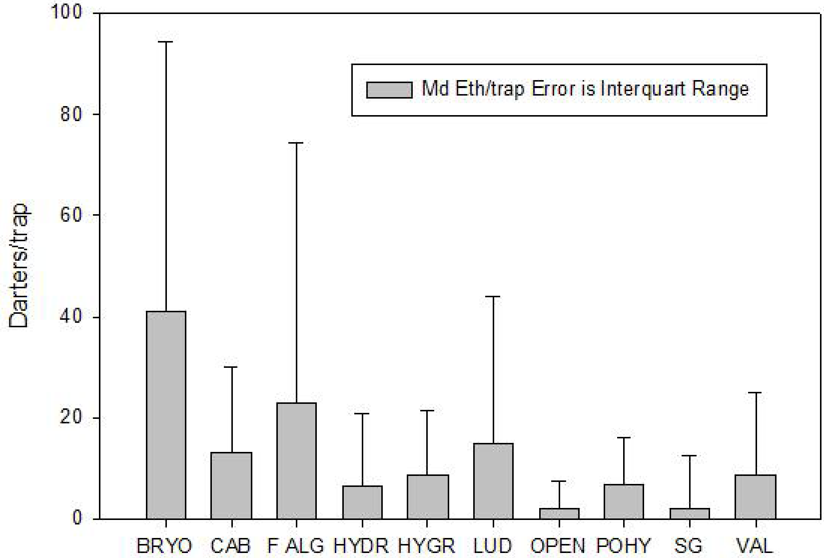



FIGURE 2-3 Number of fountain darters found per type of submerged aquatic vegetation. BRYO = bryophyte; CAB = Cabomba; F ALG = filamentous algae; HYDR = *Hydrilla*; HYGR = *Hygrophila*; LUD = *Ludwigia*; OPEN = no vegetation; POHY = *Potamogeton/Hygrophila*; SG = *Sagittaria;* VAL = *Vallisneria*. SOURCE: Committee manipulation of Edwards Aquifer Authority data.

total discharge above 140 cfs with a minimum of 45 cfs that is not to exceed six months in duration, followed by at least 80 cfs for three months. Maintaining certain minimum and long-term average flows is necessary to ensure that the vegetation habitat is healthy and that conditions (i.e., water velocities, depths) are conducive for growth, reproduction, and survival of the fountain darter.

The water quality component of the biological objective is to maintain surface water quality (e.g., conductivity, pH, turbidity) within 10 percent of the historical daily averages; instantaneous measures of dissolved oxygen (DO) will always exceed 4.0 mg/L, and temperatures will be cooler than 25°C. The water quality objective is intended to ensure stable conditions for the fountain darter, which are associated with successful reproduction.

### Monitoring, Modeling, and Applied Research

As one of the most studied of the covered species, there are long-term monitoring datasets, population modeling, and process studies available for the fountain darter. The monitoring information for the fountain darter has been well described (including in NRC, 2015), and the data are routinely analyzed for use in HCP Annual Reports and recently in exploratory analyses (e.g., Beaver Creek Hydrology, 2018; Perkin et al., 2018). Compared to dip-net data, the drop-net data are the best data to use to look for spatial and temporal trends in the fountain darter and for determination of fish densities (medians) by vegetation type. The drop net captures juveniles and adults. The recent development of an EAA database is a major step toward allowing for the merging of datasets and performing more integrative analyses.

An individual-based population model has been developed for the fountain darter in the LTBG reaches of both systems (NASEM, 2017). There remain some technical issues that cause the Committee to limit their consideration of the use of the model to a very specific subset of the many possible questions. EAA staff and the Committee have discussed these restrictions on using the model in detail. The population model is now being maintained by EAA staff (transferred from the model developers to EAA) and they are evaluating how to use the model to address questions about flow effects on habitat and fountain darter population dynamics. There are also process studies on fountain darters available as part of the Applied Research Program and other papers and theses.

In general, the site-specific information available to address the charge questions about the fountain darter is quite extensive and should allow for some degree of quantitative assessment. In the Committee's experience, the availability of tools (data, models) for the fountain darter is greater than in many similar analyses of covered species elsewhere. However, the degree of analyses has been limited to mostly simple graphical presentations of the monitoring data, and the process studies are done as specific issues arise rather than as a broader strategic approach. With the recent development of a database and several projects designed to explore the data, EAA has begun to make significant progress in integrating the fountain darter data with other monitoring data. The development of the population model was very effective in forcing the synthesis and integration of the available information into a single quantitative and full life-cycle platform. The population modeling as an integration of available information and the identification of critical gaps is an opportunity that should be leveraged. Further analyses of the monitoring and process studies for the fountain darter are warranted as the HCP enters Phase 2, which provides an opportunity to focus on compliance with biological goals and redirection of restoration efforts.

## TEXAS WILD RICE

### Description and Life History

Texas wild rice (*Zizania texana* Hitchcock) is an aquatic perennial grass inhabiting only the headwaters of the San Marcos River in Hays County, Texas (Poole and Bowles, 1999). The vegetative portions of *Z. texana* do not stand erect; instead, its 1- to 2-m-long linear, ribbon-like leaves lie decumbently semi-submerged in the shallow streambed (Terrell, 2007). More northern-adapted species of *Zizania* range from Quebec southward to northern Florida and westward to Louisiana. It now appears that *Z. texana* is a disjunct species that was stranded during the last glacial retreat and subsequently adapted to the presently hot, dry Texas summers—by assuming a more submerged habitat than its more northerly counterparts (Xu et al., 2010, 2015).

Texas wild rice reproduces both sexually and asexually. It goes through sexual reproduction typical of most angiosperms, and has male and female portions on the same panicle, which is not submerged. Female flowers mature on the emerged culms in the river after male flowers (located on the same panicle), which promotes outcrossing. When the male pollen grains are mature, they are distributed via wind, and a small percentage land on stigmatic surfaces of the ripe female florets and grow down the style to fertilize the ovary, forming the grain (caryopsis). Following fertilization, seeds mature when dormancy is broken and form the radicle and plumule, which develop rapidly into roots and shoots. The seeds remain viable for less than a year and do not form a "viable seed bank" in the sediments, unlike many wetland species. Thus, Texas wild rice depends entirely on new seeds being produced every year to complete the cycle of sexual reproduction. This trait makes it almost impossible to store seeds for a number of years (as is the case for maize, wheat, and rice). On the other hand, asexual reproduction typically depends on rhizome extensions derived from a single genetic source. The degree to which particular species depend on sexual versus clonal growth for recruitment, expansion, and maintenance of populations is often determined by environmental conditions (e.g., temperature and flow). The advantage to having both modes of reproduction is that if sexual reproduction fails, recruitment can continue using rhizomes. The downside of asexual reproduction is that if it persists for long periods, it can result in populations with very low diversity. Recent genetic studies (Xu et al., 2010, 2015; Wilson et al., 2017) suggest that Texas wild rice is remarkably robust, which is extremely important for its small geographic coverage over past decades.

When first described by Albert S. Hitchcock (1933), *Z. texana* was reported to be thriving in the upper San Marcos River where it benefited from the springs associated with the Edwards Aquifer (Bowles and Arsuffi, 1993). Despite its modest size (approximately 11 km in length), the San Marcos system was still an excellent habitat for a rich assortment of species in the early 1930s. However, after the installation of a series of five dams, the flow regime in the river became modulated and changed the physical habitat, which some have attributed to the decline of *Z. texana* in the San Marcos River. For example, Power (1996) reported that *Z. texana* densities were highest in fast-flowing segments (0.40–0.49 m/s) compared with the moderate-flow (0.12–0.24 m/s) or slow-flow (0.05–0.12 m/s) areas that became common after the dams were built. Spring Lake Dam has effectively trapped fine-grained sediments, while sandy sediments have accumulated below it, compromising the habitat suitability for *Z. texana*, which prefers organic substrates between 0.8 and 2.8 percent carbon for optimal growth (Rose and Power, 2001). Regulating flow has created patchy turbidity conditions, which can impact photosynthesis of *Z. texana*. Unsurprisingly, Poole and Bowles (1999) found Texas wild rice to occur at sites with high water clarity. They also found that calcium and sulfur dioxide concentrations were elevated on non–wild rice transects and hypothesized that this was associated with suburban and urban runoff from the City of San Marcos and other nonpoint sources, including agriculture. More recently, the high level of recreation on the San Marcos River, including kayaking and canoeing, snorkeling, SCUBA, and tubing, has been identified as a stressor on Texas wild rice. These activities can mechanically tear the delicate leaves of the Texas wild rice plants in meter-deep waters, such that recreation management is critical to the recovery of the species (EARIP, 2012).

Temperature is an essential consideration for *Z. texana*, since it is living far out of the normal range for this genus. This is a critical concern because the cool water provided by the Edwards Aquifer can keep weedy exotics from out-competing *Z. texana*. Plants of the genus *Zizania* photosynthesize via the $C_3$ pathway, which is adapted to cooler conditions. Virtually all $C_3$ plants utilize only the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) to fix carbon dioxide in the mesophyll of green leaves (i.e., via the Calvin cycle). When temperatures are elevated, RuBisCO makes use of oxygen by producing an unusable byproduct, glycolate, via photorespiration. Thus, Texas wild rice actually begins to lose considerable amounts of energy, particularly if internal leaf temperatures rise over 25°C (Poole and Bowles, 1999). On the other hand, $C_4$ grasses, such as maize and sugarcane, photosynthesize under hotter conditions (25°–35°C) by capturing carbon dioxide in the mesophyll and preventing it from being respired in a back-reaction termed photorespiration (Taiz et al., 2014).

In addition to the effects of temperature, many species of SAV can readily use bicarbonate ions present in lakes and stream waters, but *Z. texana* cannot (Power and Doyle, 2004). Thus, weedy SAV species, such as *Hydilla verticillata* and *Hygrophilla polysperma*, would be expected to have a competitive advantage over *Zizania* whenever the latter becomes starved for carbon, when pH exceeds 8.5 (Wetzel and Likens, 1991). Indeed, *Hydrilla verticillata* can still photosynthesize when pH exceeds 10 in the freshwater portions of the Chesapeake Bay (Staver and Stevenson, 1995). On the other hand, Rose and Power (2001) have measured photosynthesis versus pH in *Z. texana* from the San Marcos River and found it dropped by a factor of 5, from 0.5 mg $O_2$ per gram of tissue per hour at pH 7.5, to less than 0.1 mg $O_2$ per gram of tissue per hour at pH 8.5. It should be noted that flow can regulate both temperature and pH in the San Marcos system, highlighting the importance of maintaining minimum flows in the San Marcos River to Texas wild rice survival.

The efficiency of carbon uptake is the foremost reason that $C_4$ species outcompete $C_3$ species when $CO_2$ levels are low (and pH is high). The significance of this mechanism should not be underestimated when assessing the prospects for the long-term survival of Texas wild rice in the San Marcos River. Nonetheless, there is one physiological factor that is favorable for Texas wild rice: it can obtain a small portion of its needed $CO_2$ from the atmosphere, and atmospheric $CO_2$ concentrations have risen globally over 100 ppm over the last century and now are over 400 ppm (Dayton, 2016). This factor may offset the temperature and pH problems of Texas wild rice survival to some degree.

Weedy bicarbonate-utilizing SAV species (including *Hydrilla*) likely invaded the San Marcos system by people emptying their aquaria. These species have a competitive advantage over *Z. texana* and other non-bicarbonate-ion–utilizing species in colonizing openings created by disturbances. This is essentially the same scenario by which *Hydrilla* invaded Chesapeake Bay headwaters in the 1980s (Staver and Stevenson, 1995). Mesocosm studies containing Texas wild rice in combination with $C_4$ plants could effectively determine the extent of competition between these species under conditions similar to those in the San Marcos River.

## Biological Goals and Objectives

The biological goals for Texas wild rice are to (1) maintain a range of areal coverage in four reaches of the San Marcos River and (2) maintain a range of percentages of the coverage in those same reaches (Table 2-2). The long-term biological goals for Texas wild rice were determined by an evaluation of (1) the maximum occupied area of Texas wild rice present in the San Marcos system over time; (2) analysis of the Hardy et al. (2010) physical habitat modeling; and (3) the 1996 FWS recovery plan goals.

The biological objectives for Texas wild rice are threefold:

1. To maintain flow in the San Marcos system, with a daily long-term average (50 years including Drought of Record) of 140 cfs and a minimum of 45 cfs (not to exceed six months in duration), followed by a minimum of 80 cfs for three months
2. To maintain minimum areal coverage in the four river reaches during the Drought of Record (at values lower than the goals in Table 2-2)
3. To establish recreation awareness, with “control” in high-quality habitat areas when flow is below 100 cfs

TABLE 2-2 Long-Term Biological Goals for Texas Wild Rice

| River Segment | Areal Coverage, $m^2$ | Reach Percentage of Total Areal Coverage |
|---|---|---|
| Spring Lake | 1,000–1,500 | n/a |
| Spring Lake Dam to Rio Vista Dam | 5,810–9,245 | 83–66 |
| Rio Vista Dam to I-35 | 910–1,650 | 13–12 |
| Downstream of I-35 | 280–3,055 | 4–22 |
| TOTAL | 8,000–15,450 | 100 |

SOURCE: EARIP (2012).

### Monitoring and Modeling

Along virtually the entire stretch of the San Marcos River, Texas wild rice is painstakingly mapped to determine the area present annually. Additionally, nonnative plant species are removed whenever possible, and Texas wild rice plants are propagated and planted in strategic areas to enhance vegetative cover in the San Marcos River system (see Chapter 4). In 2017, there were 17 new stands in the river, and there was a threefold increase in Spring Lake where SCUBA is routinely employed for monitoring and planting efforts. Since the last total vegetation sampling of SAV carried out during the 2013 drought, Texas wild rice has expanded by an estimated 7,963 $m^2$ through planting and natural dispersal. Over the last year alone (2017) Texas wild rice coverage grew by an estimated 3,800 $m^2$ in the river (Blanton and Associates, 2018). Every reach of the San Marcos River appears to have gained Texas wild rice.

A detailed process-driven ecosystem model was created for SAV with eventual applicability to Texas wild rice, as discussed in great detail in NASEM (2017). Unfortunately, the SAV model has not progressed to a point where it can be utilized by the Committee to address its statement of task.

## COMAL SPRINGS RIFFLE BEETLE

The Comal Springs riffle beetle (CSRB), *Heterelmis comalensis*, was federally listed as an endangered species in 1997. The background and ecology of the CSRB are discussed in the HCP (EARIP, 2012) as well as in the two previous Committee reports (NRC, 2015; NASEM, 2017). The discussion below is meant to build on those reports and synthesize recent studies providing new biological and ecological information relevant to how the activities of the HCP will protect the CSRB and achieve its biological goals and objectives.

## Description and Life History

At the initiation of the HCP, very little was understood about the life history and population biology of the CSRB, its optimal water quality conditions, and general distribution within the Comal Springs system. Hence, in an effort to better understand the habitat, ecology, and population biology of the CSRB, the Applied Research Program has focused several projects on the beetle (see Table 5-3 in NASEM, 2017, for a recent review; BIO-WEST, 2016, 2017; Nowlin et al., 2016a,b). The results of those projects inform the discussion below.

Most of the natural history knowledge about CSRB has been generated from observing and collecting beetles from three areas considered to have suitable habitat—Spring Run 3, the Western Shoreline, and the Spring Island area, although some specimens were collected from headwaters of the San Marcos River. From these studies, it was generally understood that the habitat for CSRB is adjacent to or within spring flow orifices and in areas of groundwater upwelling with silt-free substrate that is often associated with leaf and wood debris and other terrestrial plant organic matter. Populations are often found at depths of 2 to 10 cm (Bosse et al., 1988 et al.), presumably in the interstitial spaces, and associated with organic matter (Brown, 1987). The CSRB is considered to be sensitive to siltation that results from sediment runoff from riparian zones adjacent to springs (RPS Espey et al., 2014). This sensitivity may be because the plastron respiration exhibited by adults might be compromised by heavy sedimentation.

The adults are presumed to be flightless, limiting the aerial dispersal of this endangered species. Interestingly, despite limited dispersal, CSRB populations are presumed to have survived the Drought of Record in the 1950s when all of the springs in the Comal system went dry for 144 days. Although it is not known how this species persisted and then recovered to repopulate the springs, this observation suggests that hyporheic habitat may act as a refuge during severe droughts. Tolerance threshold values of the CSRB to temperature and DO are generally not exceeded in the Comal springs (Nowlin et al., 2016a).

Populations of the CSRB have been reported to have overlapping generations and asynchronous emergence not associated with seasonal changes in weather (Bowles et al., 2003; Cooke, 2012). However, there has been limited information from field studies to describe the length or natural mortality of each development stage (egg, larva, pupa, and adult), or how each stage responds to changing environmental conditions, such as reduced flow. As discussed below, in new laboratory studies, researchers have now determined methods for sexing adults without dissection. This is an important step in understanding life cycle and biological characteristics, including the time of egg incubation, number of instars, length of each instar, habitat of pupation, length of metamorphosis to the adult stage, adult longevity, mating, and oviposition.

In lab experiments to determine egg oviposition preferences, BIO-WEST (2017) reported that 82 percent of eggs were laid on leaves and that egg production declined with increasing time of adult captivity. The number of eggs per pair of adults ranged, on average, from 0.3 to 17.8 and depended on both the mating substrate and adult survivorship. Egg incubation lasted an average of three weeks without diapause. It was concluded that treatment substrate (e.g., cotton, leaf, or rock) did affect hatching success, with the highest success on cotton cloth substrates. Previous studies have shown lab colony survivorship to be highly variable (BIO-WEST, 2014) and low (< 50 percent) after 60 days, even under preferred temperature and oxygen conditions (Nowlin et al., 2016a). BIO-WEST (2017) found that after the eggs hatched into larvae, CSRB development required seven instars and took approximately four months to the sixth instar and at least another four months for the seventh instar to complete development. The time to pupation has not been reported in detail. However, in a pilot laboratory study, after four months of late instar development, up to 56 percent of larvae pupated and adults were observed to emerge from puparia after about a month. The adult longevity is considered to be one year, and so the full life cycle of laboratory-reared populations is estimated to be two years (BIO-WEST, 2017). These efforts have revealed that there is substantial mortality among all life stages when raised in the laboratory. A recent tour of the U.S. Fish and Wildlife refugia facilities revealed mortality rates greater than 50 percent, leaving a level of survivorship that could jeopardize future husbandry efforts.

The lab studies associated mating, egg laying, and larval development with the presence of organic matter, such as leaves, suggesting an ecological coupling of CSRB larvae and adults with riparian-derived detritus in the Comal system. The preferred habitats are substrates that accumulate substantial amounts of coarse organic matter in the form of leaves and small branches. It is thought that these course organic food resources may also serve as habitat. In an effort to better understand this association, stable isotopes were used to identify primary food resources of the CSRB and potentially link them to the primary habitat (Nowlin et al., 2016b). Stable isotope profiles confirmed that CSRB feed on terrestrial-derived course particulate organic matter that is often found at springheads. Importantly, these new findings indicate a trophic connection between riparian conditions and CSRB that could affect the population biology in ways relevant to HCP conservation measures. Disconnecting the CSRB from its primary food sources could negatively affect the habitat suitability and population levels of this listed species. It is unclear how the riparian minimization and mitigation (M&M) measures will affect the quantity and quality of the course particulate organic matter that accumulates in the beetles' habitat. Better understanding this issue is an area of needed research in order to gain more confidence in the riparian restoration activities of the HCP.

### Biological Goals and Objectives

The long-term biological goals for the CSRB are to (1) maintain silt-free gravel and cobble substrate in ≥ 90 percent of three areas in the Comal system and (2) maintain specific median beetle population densities (as measured by numbers per lure) in the same three areas. The areas are Spring Run 3 (≥ 20 CSRB/lure), the western shoreline of Landa Lake (≥ 15 CSRB/lure), and Spring Island (≥ 15 CSRB/lure). The locations of the monitored habitats for these biological goals are shown in Figure 2-4.

The rationale for the required beetle abundances is not well developed in the HCP (EARIP, 2012), but they appear to be greater than or equal to the median abundances observed during the EAA Variable Flow Study (BIO-WEST, 2011a). This presents a problem because during the Variable Flow Study and until 2016, the cotton-lure methodology for sampling the CSRB was without a standard operating procedure, creating uncertainty in the measured values. Regarding the biological goal of maintaining silt-free substrate, it should be noted that there have been no quantitative studies that associate variation in silt-free habitat with CSRB population estimates. A worthy project for the Applied Research Program would be to determine how sedimentation of habitat directly (e.g., habitat suitability) and indirectly (e.g., food resource changes) affects CSRB populations, and how these sedimentation rates are related to riparian buffer conditions.

As with the other listed species, the biological objectives for achieving the long-term biological goals for the CSRB have three components. The flow component of the objective is to maintain a long-term average total Comal Springs discharge above 225 cfs with a minimum of 30 cfs that is not to exceed six months in duration, followed by at least 80 cfs for three months (the same as for the fountain darter). The water quality component of the objective is to maintain water quality issuing from the spring openings within 10 percent of historical conditions at the three study locations.

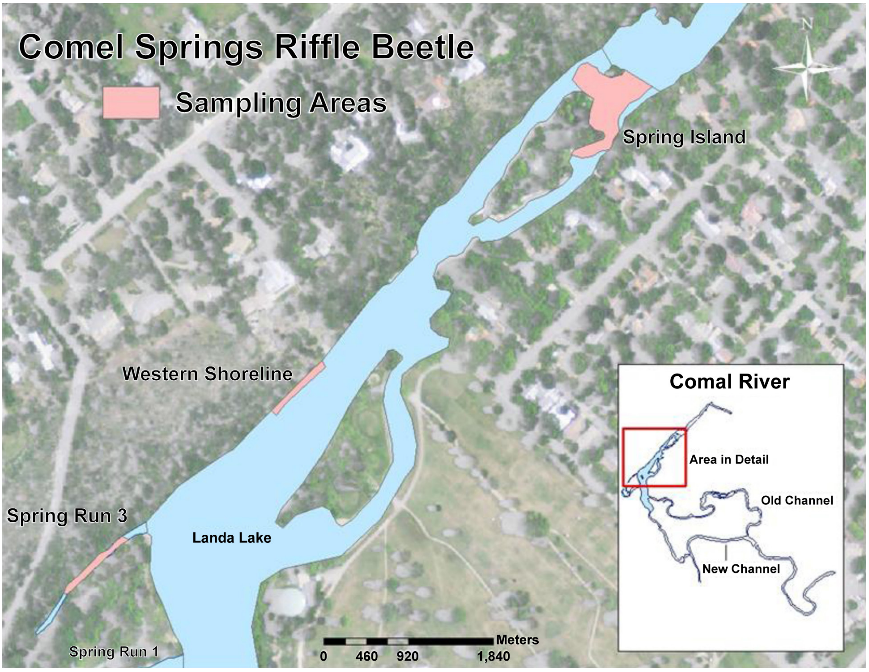



FIGURE 2-4 Three locations in the Comal system where the Comal Springs riffle beetle is monitored for compliance with long-term biological goals. SOURCE: EARIP (2012, Fig. 4-2).

The habitat component of the objective is to restore riparian habitat adjacent to spring openings to reduce siltation.

## Monitoring

CSRB populations are monitored in the three study reaches of the Comal Springs system shown in Figure 2-4: Spring Run 3, the western shoreline of Landa Lake, and the Spring Island area. The populations are collected periodically each year using a cotton-lure approach that provides qualitative estimates of both larvae and adults, but cannot provide true density estimates (as discussed at length in NRC, 2015, and NASEM, 2017).[2] Each lure is constructed of 200-thread-count white cloth of 60

[2] A recommendation from NRC (2015) was to better quantify CSRB population densities and/or calibrate the cotton-lure method of sampling so that it could potentially be an efficient and reliable way to estimate populations. "The inability to calibrate the cotton-lure method of sampling with any real densities of the CSRB in the system is a considerable weakness, making

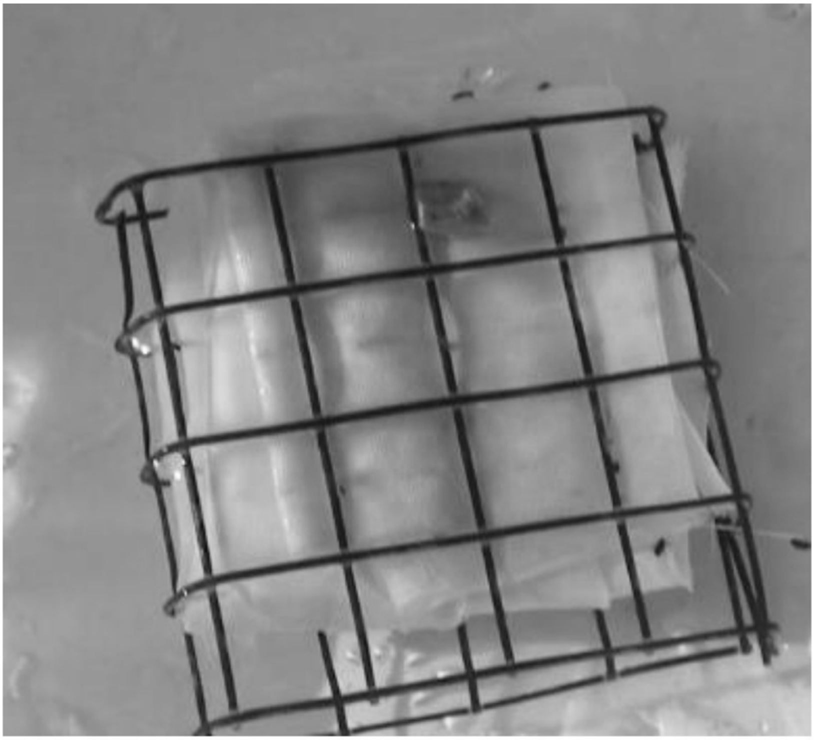


FIGURE 2-5 A representative cotton lure with some biofilm development used for enumerating Comal Springs riffle beetle. SOURCE: EAHCP (2016).

percent cotton and 40 percent polyester cut into 15- × 15-cm pieces and then folded into a 4- × 4- × 1-cm lure and placed inside a galvanized wire cage (Figure 2-5). The lures are deployed approximately 10 cm downstream of spring orifices and upwellings for passive colonization of larvae, pupae, and adults of CSRB, in addition to other invertebrates. For each monitoring event in 2016, it was reported that ten lures per study reach were placed downstream of ten individual flowing spring orifices with visible flow and then incubated for approximately four weeks (BIO-WEST, 2016).

A standard operating procedure (SOP) for the cotton lure approach was introduced during the fall 2016 sampling event. The SOP provides a

the representativeness of this sampling approach for estimating population densities unknown and making monitoring for CSRB population estimates difficult if not impossible to achieve" (NASEM, 2017). In response, a Standard Operation Procedure for how to deploy, retrieve, and score cotton lures when collecting CSRBs was created, as discussed in the main text.

standard approach to deploy, incubate, harvest, and collect beetles from the lures, taking care to note any issues of the lures and other habitat characteristics or observations that may affect monitoring (EAHCP, 2016). All CSRB (both larvae and adults) and any Peck's Cave amphipod or *Microcylloepus pusillus* are counted, and all organisms are carefully released back into the spring using mask and snorkel, although there is no mention of how well these returned organisms take hold and re-inhabit the substrate.

The sampling effort and selection of flowing spring openings for sampling are important aspects of CSRB monitoring, in that the sampling should occur twice per year and be done during the same months each year. From data provided to the Committee, it is clear that the sampling effort (in terms of frequency and number of samples per reach) is different among years, such that the number of lures used to generate the annual median values is highly variable among years. Further, the approach to spring selection for sampling should be random within each reach to avoid any bias toward certain springheads that are located in different areas of each reach. Currently within the annual biomonitoring reports, spring orifice selection is not described in any detail. Are all spring orifices mapped prior to lure deployment, and then ten openings randomly selected? Or are flowing spring openings selected in the sequence that they are found and then sampled? These are important questions that influence how the data generated from each sampling event should be analyzed and interpreted for compliance purposes.

Finally, while using median values to define the biological goals is adequate given the qualitative nature of sampling and zero-abundant data, a well-designed and articulated approach to calculating the annual median values is needed. The current method is to pool all samples from all sampling events within each reach to calculate the annual median for each reach, which could be problematic if the sampling effort is not equal and consistent from one year to the next. Based on the information provided in the most recent biomonitoring report, it is difficult to know if zero values are used in the calculation of the median.

## SAN MARCOS SALAMANDER


### Description and Life History

The San Marcos salamander (*Eurycea nana*) is a small (~40–55 mm total length), fully aquatic, obligatory paedomorphic (retaining juvenile morphology) salamander. Individuals have a dark brown back, a whitish or yellow belly, dark rings around their eyes, and rows of small spots down their sides. They retain prominent, external gills throughout life (Petranka, 1998). San Marcos salamanders are one of approximately 15 closely related species (a single monophyletic lineage) of spring- and cave-dwelling salamanders within the family Plethodontidae (lungless salamanders), and this lineage is endemic to central Texas (Chippindale et al., 2000; Chippindale, 2005).

Little is known about the species life history except what has been gleaned from observations and experiments with captive individuals. Although reproduction has never been observed in the wild (Fries, 2002), it is certainly aquatic. Average size of seven clutches deposited by captive females was 35 eggs, with a range of 2 to 73 (Najvar et al., 2007). In captivity, females attach eggs to aquatic moss, filamentous algae, and rocks (Chippindale and Fries, 2005). In the wild, they probably lay eggs among rocks at spring vents (Nelson, 1993). Males and females both reach sexual maturity around 20 mm (snout-vent length).

*Eurycea nana* are able to detect chemical cues in the water and elicit behavioral responses to these signals. For example, *E. nana* exposed to water containing chemical cues from predatory fish (i.e., *Lepomis* sp. and *Micropterus salmoides*) significantly reduced their activity as an antipredator response (Epp and Gabor, 2008; Davis et al., 2012). These salamanders also rely strongly on chemical cues to recognize members of the opposite sex (Thaker et al., 2006).

Because of their size and aquatic existence, San Marcos salamanders feed on small invertebrates that inhabit the SAV frequented by the salamanders. Tupa and Davis (1976) list midge larvae and pupae, as well as amphipods, as being the most commonly found food items in the gastrointestinal tracts of salamanders they collected. Sunfish, catfish, and crayfish are presumed to be the major predators of *E. nana*. To elude predators and avoid detection, the salamanders hide under rocks, among gravel, and in SAV.

San Marcos salamanders have an extremely limited geographic range but are locally abundant. They inhabit spring outflows throughout Spring Lake and they also occur in the San Marcos River a short distance downstream from the Spring Lake Dam spillway (with both areas being designated by the FWS [1978, 1995] as critical habitat). There are two estimates of population size for the species. Tupa and Davis (1976) estimated a population size of 20,880 based on systematic sampling at numerous sites along the north bank of Spring Lake. Density of salamanders was estimated to be 116 individuals per square meter. A second estimate of population size (Nelson, 1993) was a population of 23,000 individuals among SAV in the same area sampled by Tupa and Davis (1976). Nelson (1993) also searched for salamanders among rocky substrates at the mouth of springs throughout Spring Lake and estimated an additional 25,000 *E. nana* there. Salamanders associated with rocky substrates below the Spring Lake Dam spillway were estimated at around 5,200 individuals. Because the salamanders are known to hide below the surface in gravel substrate, Nelson's estimates are thought to be conservative (FWS, 1995).

San Marcos salamanders have an extremely restricted geographic range and only occur in the area of spring outflows of the San Marcos system. Rocky substrates, especially in close proximity to spring outflows, and aquatic macrophytes are important microhabitats for San Marcos salamanders. They are most often found in *Lyngyba* sp. (a filamentous blue-green algae) and the aquatic moss *Leptodictyum riparium* (Tupa and Davis, 1976). Aquatic vegetation provides cover for the salamanders to avoid predators, and it is where the salamanders find their invertebrate prey. Salamanders also seek refuge under rocks that sit on top of sand and gravel. Areas lacking vegetation with muddy or detritus-laden substrates are not suitable habitat (FWS, 1995).

Water emanating from the San Marcos springs system is thermally stable around 21°–22°C, and this is presumed to be the preferred water temperature for *E. nana*. Nonetheless, experiments conducted at the San Marcos National Fish Hatchery and Technology Center estimated the critical thermal maximum ($CT_{max}$) for the species at 36°–37°C (Berkhouse and Fries, 1995). Also noteworthy is the study by Norris et al. (1963), which compared oxygen consumption rates among three Edwards Plateau *Eurycea* species, including *E. nana*, at varying temperatures (15°, 20°, 25°, and 30°C). About half of the San Marcos salamanders tested at 30°C died after two hours of exposure.

Because San Marcos salamanders require clean, clear water to persist, ensuring adequate water quality is mentioned as a conservation concern in all documents that specifically address conservation of the species (FWS, 1996; Chippindale and Price, 2005; EARIP, 2012). Nonetheless, how changes in nutrients, organic compounds, herbicides and pesticides, as well as metals affect San Marcos salamanders is unknown and in need of study.

Maintaining adequate spring flow is identified as the main priority and conservation issue for the San Marcos salamander (FWS, 1996; Chippindale and Price, 2005; EARIP, 2012). FWS (1996) states that a spring flow rate of 60 cfs in the San Marcos system is "needed to prevent take, jeopardy, or adverse modification of critical habitat." Nonetheless, San Marcos salamanders persisted through the 1950s during the Drought of Record when flow dropped to 46 cfs. The species likely experienced a significant population decline during this event. Adequate flow of water adjacent to spring vents in Spring Lake precludes buildup of detritus, maintains clean sand and gravel substrates, and facilitates the growth of aquatic macrophytes that provide food and shelter for San Marcos salamanders (Tupa and Davis, 1976).

## Biological Goals and Objectives

The long-term biological goals for the San Marcos salamander address habitat quality and population density. The habitat goal requires that silt-free gravel and cobble substrates be maintained at the three main sites where the species has been shown to occur in the greatest densities in the past 50 years: hotel site, riverbed site, and Spring Lake Dam site (Figure 2-6). The goal is to maintain habitat quality at ≥ 90 percent of each study area. The density goal sets specific targets for median density of salamanders at each of the three sites (Table 2-3).

Designation of specific population densities at the three sampling reaches was based on data collected from 2000 to 2010 during the EAA's Variable Flow Study (EARIP, 2012, Tables 4-26, 4-27). Densities of salamanders estimated across the three sites during this period, which included routine sampling and additional sampling during low- and high-flow events, varied considerably within and among years. Therefore, the EAA used

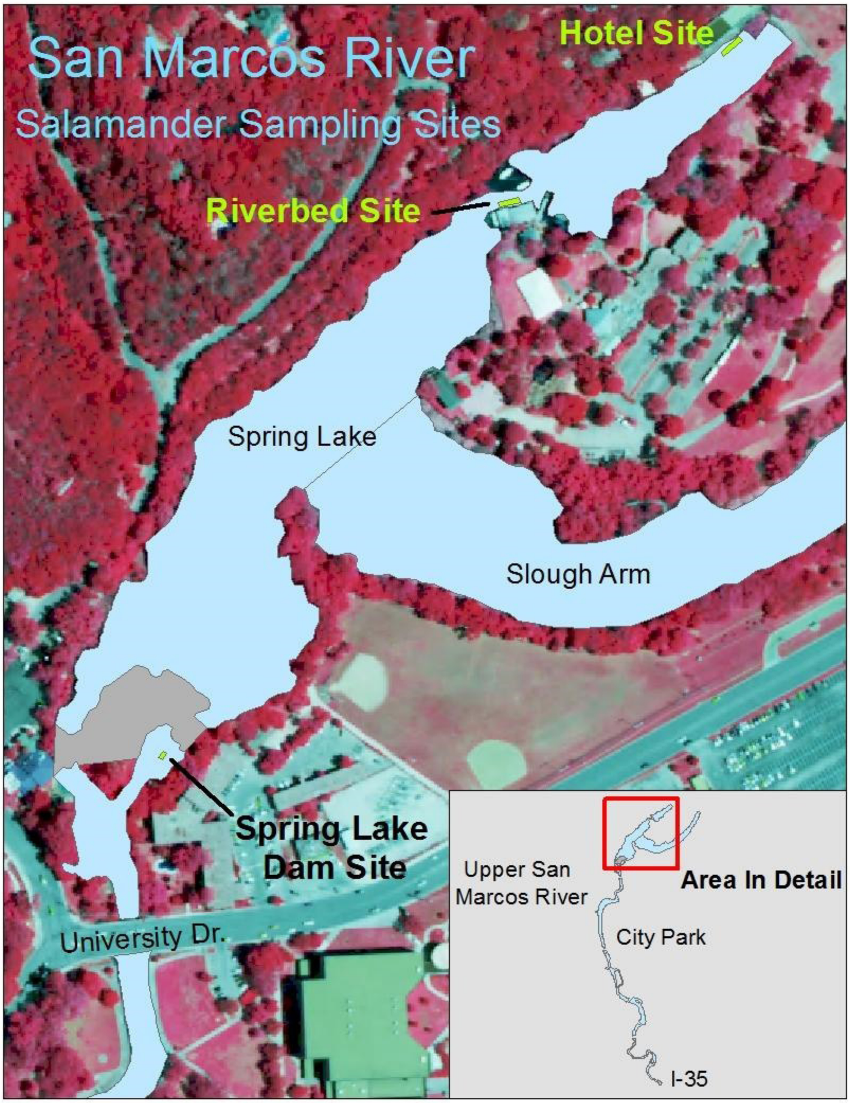



FIGURE 2-6 Long-term biological goal reaches for the San Marcos salamander: hotel site, riverbed site, and Spring Lake Dam site. SOURCE: Furl (2017).

TABLE 2-3 Long-Term Biological Goals for San Marcos Salamanders

| Study Reach | Habitat Quality | Salamander Density |
|---|---|---|
| Hotel Site (Spring Lake) | Maintain ≥90% of site as silt-free gravel and cobble | ≥15 salamanders/m$^2$ |
| Riverbed Site (Spring Lake) | | ≥10 salamanders/m$^2$ |
| Eastern Spillway (just below Spring Lake Dam) | | ≥5 salamanders/m$^2$ |

SOURCE: EARIP (2012).

"professional judgment" in its decision to designate median density as the population-based biological goal for the San Marcos salamander. Specific density values set for the three sites were based on data from 2000 to 2010 and seem reasonable and defensible.

Maintaining silt- and detritus-free gravel and cobble bottom substrate conditions was identified in the species recovery plans as being crucial for the persistence of the salamander (FWS, 1996). The emphasis on this specific habitat parameter at the three locations identified in the HCP is apparently based on the research of Tupa and Davis (1976) and Nelson (1993). Given the importance of SAV as cover and a source of food for San Marcos salamanders, there was some discussion of establishing SAV targets in the three sampled reaches (EARIP, 2012, p. 4-34), but this idea was dismissed in favor of the simpler target of "maintaining silt-free substrates (gravels and cobbles) over greater than or equal to 90 percent of the fixed sampling reaches." The designation of 90 percent of the sampling reaches as silt-free appears somewhat arbitrary and a "best guess" due to the complexity of the salamander's use of gravel substrates and macrophytes.

Three biological objectives are identified to achieve the long-term biological goals. Two of the objectives—(1) aquatic gardening at the riverbed and hotel sites and (2) regulation of human recreation activity at the spillway site—are odd because as stated they are virtually identical to certain M&M measures. A third, flow-related objective is the same as for Texas wild rice: a long-term average of 140 cfs and a minimum of 45 cfs. Note that there is no water quality component of the biological objective for San Marcos salamanders.

## Monitoring and Applied Research

San Marcos salamanders have been monitored at three sample reaches (hotel area, riverbed, and eastern spillway) two to four times a year since fall 2000. Although estimated densities vary considerably within and among years, as well as among the three sampling reaches, average densities over the past 15 years are largely consistent with the LTBG density targets. Note that, like the CSRB, there is no monitoring to determine compliance with the goal of having silt-free gravel.

Salamander surveys are routinely conducted twice a year—once in spring (April–May) and again in fall (October–November)—with additional surveys conducted during periods of especially high or low flow. Considering the fact that San Marcos salamanders do not migrate and are active year-round in the thermally stable waters of the San Marcos system, sampling salamanders twice a year (spring and fall) is appropriate for monitoring. In fact, the FWS Recovery Plan (FWS, 1995) recommends sampling for salamanders only once a year. It seems unlikely that salamander detection probability varies much throughout the year, but that is an assumption that could be tested.

Visual searches are made for salamanders by trained personnel via snorkeling or SCUBA. Observers swim over historically set transects and conduct three, 5-minute timed surveys per sample area. They visually scan for salamanders and also turn over rocks (>5 cm wide) to look for animals. Salamanders are counted and substrate type is noted. Surveys are conducted in sections of each reach that are free of submerged macrophytes. Areas within or immediately adjacent to each sampling reach that are covered with dense macrophytes and algae are purposely avoided. It is possible that density estimates are inflated because of this sampling protocol; that is, it seems reasonable that experienced divers and snorkelers would learn which rocks are likely to harbor salamanders and preferentially choose those rocks to sample.

The current sampling design does not allow density estimates to be extrapolated across the entire Spring Lake area or the smaller spillway site. Therefore, there is no accurate way to get an estimate of the entire salamander population. To supplement the current sampling, an additional protocol that uses occupancy estimation could be designed for the San Marcos salamander. Such a protocol would provide estimates of proportion of area occupied as well as detection probability and allow inference of salamander population trends across more of their potential habitat within Spring Lake. A collaboration between the EAA, biologists from the FWS, and the U.S. Geological Survey Amphibian Research and Monitoring Initiative[3] could be

[3] See https://armi.usgs.gov/.

undertaken to design a robust occupancy estimation protocol. Furthermore, the statistical methods reviewed by Denes et al. (2015) could shed light on the extent of error associated with the current sampling protocol.

Apparently, the only EAA research activities to date focused on the San Marcos salamander are development of husbandry practices as part of the captive assurance colony Long-Term Refugia Program. The San Marcos salamander is listed as a Tier 2 priority (among four priority tiers) for additional research under the scope of work for the Long-Term Refugia Operation implemented between the EAA and the FWS on January 1, 2017. Subtask 2.3 of this scope of work directs the FWS to conduct research on the species' physiology, environmental requirements, and life history, among others.

Since ensuring that silt-free gravel is a stated biological goal in the HCP, there is an expectation that the EAA will quantify this parameter at least annually. However, data on the extent of silt-free gravel are not presented in annual HCP or biomonitoring reports.

## OTHER COVERED SPECIES

Other covered species include the Comal Springs dryopid beetle, Peck's Cave amphipod, Edwards Aquifer diving beetle, Texas troglobitic water slater, Texas blind salamander, Comal Springs salamander, and San Marcos gambusia.

### Description of the Organisms

The **Comal Springs dryopid beetle** (*Stygoparnus comalensis*) is a subterranean species inhabiting the Comal Springs system that was listed as endangered in 1997 (FWS, 1997). Comal Springs dryopid beetles are small (~3 mm), slender, reddish-brown beetles with vestigial eyes. Because of its inability to swim, the Comal Springs dryopid beetle is restricted to the headwaters of the springs and spring upwelling areas (EARIP, 2012). The subterranean nature and the habitat restriction (i.e., headwaters and upwelling areas of the spring) of the Comal Springs dryopid beetle suggest that it does not require substantial surface discharge from springs to survive and presume that spring flow (of sufficient water quality) that continually covers the spring orifice should prevent long-term detriment to the population (EARIP, 2012).

**Peck's Cave amphipod** (*Stygobromus pecki*) is a subterranean species found in Comal and Hueco springs. This species was first described using specimens collected from Comal Springs in 1964 and 1965 (Holsinger, 1967). The Peck's Cave amphipod was listed as endangered in 1997 (FWS, 1997). Like all members of the genus *Stygobromus*, Peck's Cave amphipods are eyeless, unpigmented, and approximately 3 mm long. It is believed that the Peck's Cave amphipod is restricted to the headwaters of the springs and spring upwelling areas (EARIP, 2012).

The **Texas blind salamander** (*Eurycea rathbuni*, previously assigned to the genus *Typhlomolge*) is a relatively large (~90–135 mm total length), unpigmented, troglobitic salamander that was listed as endangered in 1967 (EARIP, 2012). Its snout is flattened and shovel-shaped, and it has small eyespots that are covered with skin. Its limbs are relatively long and thin. It has a prominent dorsal tailfin that extends from the rear legs to the tip of the tail. It is permanently aquatic and possesses enlarged reddish-colored gills (Petranka, 1998; Powell et al., 2016).

The **Edwards Aquifer diving beetle** (*Haideoporus texanus*), also known as the Texas cave diving beetle, is a small (typically less than 13 mm), blind, unpigmented, elongate, oval-shaped, and somewhat flattened member of the family Dytiscidae (Young and Longley, 1976). This species is restricted to the subterranean waters of the Edwards Aquifer in Hays and Comal Counties, where it has been collected from artesian wells and from Comal Springs (EARIP, 2012). The Edwards Aquifer diving beetle is not currently listed as endangered but is listed as under review by the FWS (2009).

The **Texas troglobitic water slater** (*Lirceolus smithii*) is a small, blind, unpigmented asellid isopod (Bowman and Longley, 1975). This species is known from two localities in Hays County—San Marcos Springs (Diversion Springs) and the artesian well that is located very close to San Marcos Springs. Specimens are rarely collected (EARIP, 2012). The Texas troglobitic water slater is not currently listed as endangered but is listed as under review by the FWS (2009).

The **Comal Springs salamander** (*Eurycea* sp.) has not been formally described as a unique species, but some authorities believe it is distinct due to restricted gene flow among other *Eurycea* of the Edward's Plateau (Chippindale, 2000; Chippindale et al., 2000; Lucas et al., 2009). In their "Partial 90-Day Finding on a Petition to List 475 Species in the Southwestern United States as Threatened or Endangered with Critical Habitat," the FWS (2009) identifies the Comal Springs salamander as *Eurycea* sp. 8. However, recent genetic research on the entire *Eurycea* complex in eastern Texas conducted at the University of Texas at Austin suggests that the salamanders inhabiting Comal Springs are a population of the Texas salamander, *E. neotenes* (D. Hillis, personal communication, February 6, 2018). That said, a study of gene flow among salamander habitat patches within the Comal Springs complex concluded that the Comal Springs salamander should be treated as a distinct management unit and a distinct evolutionarily significant unit for conservation purposes (Lucas et al., 2016). The Comal Springs salamander is not currently listed as endangered but is listed as "under review" by the FWS.

The **San Marcos gambusia** (***Gambusia georgei***) is a member of the family Poeciliidae. This small fish (2.5–4 cm as adults) was first described as one of three native *Gambusia* species in the San Marcos River by Hubbs and Peden (1969). Historically, San Marcos gambusia inhabited shaded, unsilted substrates in quiet, shallow, thermally constant, open waters adjacent to areas of flow (EARIP, 2012). The FWS designated the San Marcos River from the Highway-12 bridge downstream to just below the I-35 bridge as critical habitat for the San Marcos gambusia (FWS, 1996).

## Biological Goals and Objectives

Ecological knowledge of the Comal Springs dryopid beetle, the Peck's Cave amphipod, the Edwards Aquifer diving beetle, and the Texas troglobitic water slater is lacking, while relatively more research on the Texas blind salamander and the Comal Springs salamander is available. Regardless of available information, there are currently no HCP long-term biological goals for these species that can be addressed with biological data (Perkin et al., 2018). Therefore, the long-term biological goals for these species focus on water quality and spring flow. The water quality goal is that water quality should not exceed a 10 percent deviation (daily average) from historically recorded water quality conditions (long-term average) within the Edwards Aquifer as measured from the spring openings at Comal Springs. This includes all water quality constituents currently measured in the EAA Variable Flow Study. The HCP states that more extensive work to evaluate and assess water quality tolerances of Comal Springs dryopid beetles and Peck's Cave amphipods will be addressed as part of the Adaptive Management Program (EARIP, 2012, p. 4-15). The current HCP Refugia program will maintain wild stock of each invertebrate and salamander species, including a genetic management plan for each, and, importantly, will allow for basic life history research that will inform capture and collection, husbandry, propagation, genetics, and reintroduction.

With respect to the spring flow requirement, it is believed that these species have the ability to retreat into subterranean refuges as spring flow declines and water levels subside into the spring vents. Nevertheless, the HCP is designed on the premise that these species require water levels adequate to support consistent spring flows. Thus, the discharge rates that are considered suitable for fountain darters (long-term average discharge of 225 cfs, minimum discharge of 30 cfs for no more than six months) are also considered suitable for these troglobitic invertebrates and salamanders (EARIP, 2012).

Because of high rates of hybridization with the western mosquitofish (*Gambusia affinis*), and the fact that no specimens have been collected since 1983, McKinney and Sharp (1995) concluded that the San Marcos River gambusia was extinct. As such, there are no stated long-term biological goals for the San Marcos River gambusia.

## Monitoring

The invertebrate species were monitored as part of the macroinvertebrate community drift-net surveys at four Comal Springs sources during 2003–2015 (the program continues today with modifications). The Comal Springs dryopid beetle and the Edwards Aquifer diving beetle were rarely captured in drift nets, whereas Texas troglobitic water slaters and especially Peck's Cave amphipods were collected in high numbers during the 12-year study period. Both the Comal Springs dryopid beetle and the Peck's Cave amphipod were considered in the recent statistical analysis of the biomonitoring datasets (Perkin et al., 2018). The primary conclusion drawn from the monitoring analysis was that both species abundance estimates were positively correlated with spring discharge rate, a pattern considered to be an artifact of higher flows forcing more animals into the drift nets. The Beaver Creek analysis documented a similar positive relationship with flow, suggesting that high flow could be related to higher DO concentrations, but the current dataset did not allow ruling out a simple artifact of higher flushing with flow. Additionally, the Beaver Creek analysis concluded that Peck's Cave amphipods were more abundant in sampling sites with higher temperatures (western upwelling), while Comal Springs dryopid beetles were more abundant in sampling sites with cooler temperatures (Spring Runs 1 and 3) (Beaver Creek Hydrology, 2018). This analysis included additional data from seven sites in the Comal and San Marcos systems during 2013–2015, although it appears that the previous conclusion was derived using Comal Springs data only.

Because the Texas blind salamander is a subterranean species that is rarely observed near the surface, except in a few caves, the EAA is not conducting any monitoring activities for this species. While it has been stated that annual monitoring would be preferred, given the cryptic natural history of the species and the difficulty encountering them, the EAA has concluded that a monitoring program for the Texas blind salamander is not practical. By contrast, Comal Springs salamanders have been monitored via visual surveys by divers or snorkelers at least twice a year since 2001. Additional surveys have been conducted during periods of especially high and low flow. Observations consist of time-constrained searches in the deeper areas of Landa Lake by biologists using SCUBA. Salamanders are also monitored by snorkelers in the following reaches of the Comal system: Spring Run 1, Spring Run 3, and the Spring Island area. During searches, biologists scan the bottom and turn over rocks. Specific locations, time, water depth, and presence/absence of SAV are noted. Numbers of Comal Springs salamanders counted during annual surveys vary considerably among sites, years, seasons, and spring flow levels. On average, more salamanders are documented at Spring Run 1 than the other spring outflow sites. Spring Island has the fewest observations over time. As demonstrated by data collected from 2002 through 2012, absolute numbers of salamanders counted (not corrected for effort) among the spring outflow sites during any given sampling period range from 0 (Spring Island) to more than 50 at Spring Run 1 (see Table 7 in BIO-WEST, 2013). There is no active monitoring program for the San Marcos gambusia.

## CONCLUSIONS AND RECOMMENDATIONS

**The habitat-based approach for the biological goals for the fountain darter (fountain darter density times submerged aquatic vegetation acreage), rather than an actual measure of fish abundance, is reasonable.** However, the use of the cumulative median density in determining whether the biological goals are being met is problematic because this metric is very insensitive to year-to-year changes in fountain darter densities. It is imperative that the EAA consider a metric that reflects fountain darter density in recent years (e.g., a running mean or median over the most recent four years, or similar) for each vegetation type and monitor it relative to an unchanging baseline (e.g., the cumulative median from the first ten years in the Variable Flow Study dataset, or other appropriate baseline data). The development of the fountain darter population model was very effective in integrating the available information and should be leveraged in the future. Chapter 5 further discusses approaches to ensure a resilient and sustainable fountain darter population.

**The biological goals for Texas wild rice are appropriate, and this species has benefited from extensive monitoring and decades of study.** The EAA and its partners have taken particular care in the overall mapping of Texas wild rice in the San Marcos River. Considerable work done over the last century has revealed the life history and physiology of Texas wild rice, which has expanded our knowledge of the genetic framework of this species and its relatives. There are still some questions about relative competition of Texas wild rice versus other native and nonnative SAV, which could be addressed with mesocosm studies.

**The long-term biological goals for Comal Springs riffle beetle density should be updated during Phase 2 of the HCP to reflect more quantitative and standardized monitoring methods.** The density goals were based on data derived from the Variable Flow Study, which used an unstandardized sampling methodology with no standard operating procedure. It would also be useful to conduct new CSRB studies under the Applied Research Program to better substantiate the biological goal of maintaining silt-free habitat. Beyond the uncertainties that went into deriving these biological goals, uncertainties associated with continued population monitoring and a lack of monitoring of the effects of riparian restoration on maintaining sufficient silt-free substrate make it difficult to understand compliance. A reevaluation of how annual median values of beetle abundance are calculated for compliance purposes is needed.

**Both biological goals for the San Marcos salamander—target densities in three reaches and maintenance of silt-free gravel—are reasonable and biologically justifiable.** In order to meet the abundance goals, the EAA should discontinue calculating cumulative median densities, which are insensitive to temporal variation in estimates of salamander densities, and instead adopt a metric that reflects salamander density in recent years. Furthermore, the EAA needs to begin monitoring adherence to the goal of maintaining silt-free substrates. Given the considerable spatial variation in salamander abundance data and the inability to accurately estimate salamander numbers, the current sampling method could be supplemented with an additional protocol that uses occupancy estimation. It is also important to eliminate any sampler biases during salamander monitoring. Finally, the San Marcos salamander would benefit from additional studies on its life history, particularly using refugia populations, similar to what has been done for the fountain darter, CSRB, and Texas wild rice and other SAV.

**The EAA should continue to collect data as possible on all other non-sentinel species with the goal of eventually being in position to test the hypothesis that the sentinel species do indeed serve as viable proxies for protecting all Edwards Aquifer species.**

## REFERENCES

Alexander, M. L., and C. T. Philips. 2012. Habitats used by the endangered fountain darter (*Etheostoma fonticola*) in the San Marcos River, Hays County, Texas. The Southwestern Naturalist 57(4):449-452.

Beaver Creek Hydrology, LLC. 2018. Statistical analysis of the San Marcos and Comal Springs aquatic ecosystems biomonitoring datasets. Edwards Aquifer Authority. http://www.eahcp.org/files/admin-records/NEPA-and-HCP/Beaver_Creek_Statistical_Analysis_of_BioMonitoring_datasets.pdf.

Becker, S., J. Lily, and C. R. Gabor. 2012. Effects of Turbidity and Visual vs. Chemical Cues on Anti-Predator Response in the Endangered Fountain Darter (*Etheostoma fonticola*). Ethology 118(10):994-1000.

Berkhouse, C. S., and J. N. Fries. 1995. Critical thermal maxima of juvenile and adult San Marcos salamanders (*Eurycea nana*). The Southwestern Naturalist 40:430-434.

BIO-WEST. 2011a. Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the Comal Springs/River Aquatic ecosystem. Final 2010 Annual Report. Edwards Aquifer Authority.

BIO-WEST. 2011b. Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the San Marcos Springs/River Aquatic ecosystem. Final 2010 Annual Report. Edwards Aquifer Authority.

BIO-WEST. 2013. Comprehensive and Critical Period Monitoring Program to Evaluate the Effects of Variable Flow on Biological Resources in the Comal Springs/River Aquatic Ecosystems. Final Report to Edwards Aquifer Authority. http://www.eahcp.org/files/admin-records/NEPA-and-HCP/Comal_Final_2012_Annual_Report_Full_(Attachment_8).pdf.

BIO-WEST. 2014. Habitat Conservation Plan Biological Monitoring Program Comal Springs/River Aquatic Ecosystem. Annual Report to Edwards Aquifer Authority.

BIO-WEST. 2016. Habitat Conservation Plan Biological Monitoring Program Comal Springs/River Aquatic Ecosystem. Annual Report to Edwards Aquifer Authority.

BIO-WEST. 2017. Comal Springs Riffle Beetle (*Heterelmis comalensis*): Life History and Captive Propagation Techniques. Final Report prepared for the Edwards Aquifer Authority, December 27. http://www.eahcp.org/files/admin-records/NEPA-and-HCP/BIO-WEST_CSRB.life.hist_FINAL_20180126.pdf.

BIO-WEST and Watershed Systems Group. 2016. Submerged Aquatic Vegetation Analysis and Recommendations. Edwards Aquifer Habitat Conservation Plan. Contract No. 15-7-HCP. June.

Blanton and Associates. 2018. Edwards Aquifer Habitat Conservation Plan. 2017 Annual Report. http://www.eahcp.org/files/admin-records/NEPA-and-HCP/EAHCPAnnualReport2017v3_20180313_Redlined_from_Blanton.pdf.

Bosse, L. S., D. W. Tuff, and H. P. Brown. 1988. A new species of *Heterelmis* from Texas (Coleoptera: Elmidae). The Southwestern Naturalist 33(2):199-203.

Bowles, D. E., and T. L. Arsuffi. 1993. Karst aquatic systems of the Edwards Plateau region of central Texas, USA: a consideration of their importance, threats to their existence, and efforts for their conservation. Aquatic Conservation: Marine and Freshwater Ecosystems 3:317-329.

Bowles, D. E., C. B. Barr, and R. Stanford. 2003. Habitat and phenology of the endangered riffle beetle *Heterelmis comalensis* and a coexisting species, *Microcylloepus pusillus*, (Coleoptera: Elmidae) at Comal Springs, Texas, USA. Archiv für Hydrobiologie 156(3):361-383.

Bowman, T. E., and G. Longley. 1975. Redescription and assignment to the new genus *Lirceolus* of the Texas troglobitic water slater, *Asellus smithii* (Ulrich) (Crustacea: Isopoda: Asellidae). Proceedings of the Biological Society of Washington 88:489-496.

Brandt, T. M., K. G. Graves, C. S. Berkhouse, T. P. Simon, and B. G. Whiteside. 1993. Laboratory spawning and rearing of the endangered fountain darter. The Progressive Fish-Culturist 55(3):149-156.

Brown, H. P. 1987. Biology of riffle beetles. Annual Review of Entomology 32:253-273.

Chippindale, P. T. 2000. Species boundaries and species diversity in the central Texas hemidactyline plethodontid salamanders, genus *Eurycea*. Pp. 149-165 *In*: The Biology of Plethodontid Salamanders. R. C. Bruce, R. G. Jaeger, and L. D. Houck (eds.). New York: Springer Science+Business Media.

Chippindale, P. T. 2005. *Eurycea rathbuni* Texas Blind Salamander. Pp. 760-762 *In*: Amphibian Declines: The Conservation Status of United States Species. M. J. Lanoo (ed.). Berkeley: University of California Press.

Chippindale, P. T., and J. N. Fries. 2005. *Eurycea nana* San Marcos Salamander. Pp. 755-756 *In*: Amphibian Declines: The Conservation Status of United States Species. M. J. Lanoo (ed.). Berkeley: University of California Press.

Chippindale, P. T., and A. H. Price. 2005. Conservation of Texas spring and cave salamanders (*Eurycea*). Pp. 193-197 *In*: Amphibian Declines: The Conservation Status of United States Species. M. J. Lanoo (ed.). Berkeley: University of California Press.

Chippindale, P. T., A. H. Price, J. J. Wiens, and D. M. Hillis. 2000. Phylogenetic relationships and systematic revision of central Texas hemidactyline plethodontid salamanders. Herpetological Monographs 14:1-80.

Cooke, M. 2012. Natural history studies on the Comal Springs riffle beetle *(Heterelmis comalensis)*. Doctoral dissertation, Texas State University-San Marcos.

Dammeyer, N. T., C. T. Phillips, and T. H. Bonner. 2013. Site fidelity and movement of *Etheostoma fonticola* with implications to endangered species management. Transactions of the American Fisheries Society 142(4):1049-1057.

Davis, D. R., K. J. Epp, and C. R. Gabor. 2012. Predator generalization decreases the effect of introduced predators in the San Marcos salamander, *Eurycea nana*. Ethology 118:1191-1197.

Dayton, L. 2016. Atmospheric carbon dioxide soars past crucial milestone. Science [May 16]; DOI: 10.1126/science.aaf5722.

Denes, F. V., L. F. Silveira, and S. R. Beissinger. 2015. Estimating abundance of unmarked animal populations: Accounting for imperfect detection and other sources of zero inflation. Methods in Ecology and Evolution 6:543-556.

EAHCP (Edwards Aquifer Habitat Conservation Plan). 2016. Comal Springs Riffle Beetle Cotton Lure SOP. http://www.eahcp.org/files/uploads/CSRB_SOP_Final.pdf.

EARIP (Edwards Aquifer Recovery Implementation Program). 2012. Edwards Aquifer Recovery Implementation Program Habitat Conservation Plan. http://www.eahcp.org/files/uploads/Final%20HCP%20November%202012.pdf.

Epp, K. J., and C. R. Gabor. 2008. Innate and learned predator recognition mediated by chemical signals in *Eurycea nana*. Ethology 114:607-615.

Fries, J. N. 2002. Upwelling flow velocity preferences of captive adult San Marcos salamanders. North American Journal of Aquaculture 64:113-116.

Furl, C. 2017. Conservation Measures, Biological Objectives, Biological Goals. Presentation to the National Academies' Committee to Review the Edwards Aquifer Habitat Conservation Plan, October 2.

FWS (U.S. Fish and Wildlife Service). 1978. Proposed Listing and Critical Habitat Determination for a Fish and Salamander. Federal Register 43:30316-30319.

FWS. 1995. San Marcos/Comal (Revised) Recovery Plan. Albuquerque, New Mexico. pp. x + 93 with 28 pages of appendices.

FWS. 1996. San Marcos and Comal Springs and associated aquatic ecosystems (revised) recovery plan. Department of Interior, Fish and Wildlife Service.

FWS. 1997. 50 CFR Part 17: Endangered and threatened wildlife and plants; final rule to list three aquatic invertebrates in Comal and Hays counties, TX, as endangered. Federal Register 62(243):66295.

FWS. 2008. Strategic Habitat Conservation Handbook: A Guide to Implementing the Technical Elements of Strategic Habitat Conservation (Version 1.0). U.S. Fish and Wildlife Service. Report from the National Technical Assistance Team. February 11, 2008.

FWS. 2009. Part 3 Department of the Interior, Fish and Wildlife Service Endangered and threatened wildlife and plants; partial 90-day finding on a petition to list 475 species in the southwestern United States as threatened or endangered with critical habitat; proposed rule. 74 74 Fed. Reg. 66866-66905 (December 16, 2009).

FWS. 2013. News Release: Service Approves Edwards Aquifer Recovery Implementation Program's Incidental Take Permit. Department of Interior. Fish and Wildlife Service.

Hardy, T. B., K. Kollaus, and K. Tower. 2010. Evaluation of the Proposed Edwards Aquifer Recovery Implementation Program Drought of Record Minimum Flow Regimes in the Comal and San Marcos River Systems. River Systems Institute, Texas State University.

Hitchcock, A. S. 1933. New Species and new names of grasses from Texas. Journal of the Washington Academy of Science 23:449-456.

Holsinger, J. R. 1967. Systematics, speciation, and distribution of the subterranean amphipod genus *Stygonectes* (Gammaridae). Bulletin—United States National Museum 259:1-176.

Hubbs, C., and A. E. Peden. 1969. *Gambusia georgei* sp. nov. from San Marcos, Texas. Copeia 2:357-364.

Labay, A. A., and T. M. Brandt. 1994. Predation by *Cyclops vernalis* on Florida largemouth bass and fountain darter larvae. The Progressive Fish-Culturist 56(1):37-39.

Lucas, L. K., Z. Compert, J. R. Ott, and C. C. Nice. 2009. Geographic and genetic isolation in spring-associated *Eurycea* salamanders endemic to the Edwards Plateau region of Texas. Conservation Genetics 10:1309-1319.

Lucas, L. K., Z. Compert, J. R. Gibson, K. L. Bell, C. A. Buerkle, and C. C. Nice. 2016. Pervasive gene flow across critical habitat for four narrowly endemic, sympatric taxa. Freshwater Biology 61:933-946.

McDonald, D. L., T. H. Bonner, E. L. Oborny Jr., and T. M. Brandt. 2007. Effects of fluctuating temperatures and gill parasites on reproduction of the fountain darter, Etheostoma fonticola. Journal of Freshwater Ecology 22(2):311-318.

McKinney, D. C. and J. M. Sharp. 1995. Springflow augmentation of Comal Springs and San Marcos Springs, Texas: Phase I - feasibility study. Center for Research in Water Resources Technical Report CRWR 247. Bureau of Engineering Research, University of Texas at Austin, TX.

Najvar, P. A., J. N. Fries, and J. T. Baccus. 2007. Fecundity of San Marcos salamanders in captivity. The Southwestern Naturalist 52:145-147.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2017. Review of the Edwards Aquifer Habitat Conservation Plan: Report 2. Washington, DC: The National Academies Press.

Nelson, J. 1993. Population Size, Distribution, and Life History of *Eurycea nana* in the San Marcos River. M.S. Thesis, Texas State University.

Norris, W. E., Jr., P. A. Grandy, and W. K. Davis. 1963. Comparative studies of the oxygen consumption of three species of neotenic salamanders as influenced by temperature, body size, and oxygen tension. The Biological Bulletin 125:523-533.

Nowlin, W. H., D. Hahn, P. Nair, and F. Alfano. 2016a. Evaluation of the trophic status and functional feeding group status of the Comal Springs Riffle Beetle. EAHCP Project No. 148-15-HCP. http://www.eahcp.org/documents/Nowlin%20et%20al.%202017%20CSRB%20FFG.PDF.

Nowlin, W. H., P. Nair, and B. Schwartz. 2016b. Final Report. Evaluation of the long-term elevated temperature and low dissolved oxygen tolerances of larvae and adult Comal Springs riffle beetle. EAHCP Project No. 146-15-HCP. http://www.eahcp.org/files/uploads/Nowlin_et_al._2017_EAA_2016_Applied_Research_-_CSRB_Long_Term_Temp_and_D....pdf.

NRC (National Research Council). 2015. Review of the Edwards Aquifer Habitat Conservation Plan: Report 1. Washington, DC: The National Academies Press.

Perkin, J. S., E. Kosnicki, and J. Jackson. 2018. Analysis of the Comal Springs and San Marcos Springs long-term monitoring dataset. Edwards Aquifer Authority.

Petranka, J. W. 1998. Salamanders of the United States and Canada. Smithsonian Institution Press, Washington, DC.

Poole, J., and D. E. Bowles. 1999. Habitat characterization of Texas wild-rice (*Zizania texana* Hitchcock), an endangered aquatic macrophyte from the San Marcos River, TX, USA. Aquatic Conservation: Marine and Freshwater Ecosystems 9:291-302.

Powell, R., R. Conant, and J. T. Collins. 2016. Peterson Field Guide to Reptiles and Amphibians of Eastern and Central North America, Fourth Edition New York: Houghton Mifflin Harcourt.

Power, P. 1996. Effects of current velocity and substrate composition on growth of Texas wild rice (*Zizania texana*). Aquatic Botany 55:199-204.

Power, P., and R. D. Doyle. 2004. Carbon use by the endangered Texas Wild Rice (*Zizania texana, Poaceae*). SIDA Contributions in Botany 21(1):389-398.

Rose, F., and P. J. Power. 2001. Continued Maintenance, Reintroduction and Research on *Zizania texana* (Texas Wildrice). Grant E#3, Report to Texas Parks and Wildlife.

RPS Espey, HEI, and BIO-WEST. 2014. 2014 Final Report for Riffle Beetle Habitat Restoration Spring Run 3 and Landa Lake Shoreline. Prepared for City of New Braunfels. December 22, 2014.

Schenck, J. R., and B. G. Whiteside. 1977. Food habits and feeding behavior of the fountain darter, *Etheostoma fonticola* (Osteichthyes: Percidae). The Southwestern Naturalist 21(4):487-492.

Staver, L. W., and J. C. Stevenson. 1995. The impacts of the exotic species *Hydrilla verticillata* on the shallows in Chesapeake Bay. Pp 364-370 in Toward a Sustainable Coastal Watershed: The Chesapeake Experiment. Proceedings of a Conference. Shady Side MD.

Taiz, L., E. Zieger, I. A. Møller, and A. Murphy, A. 2014. Plant Physiology and Development, sixth edition. Sunderland, Massachusetts: Sinauer Associates.

Terrell, E. E. 2007. Zizania. Pp. 47-51, *In*: Flora of North America, Vol. 24. UK: Oxford University Press.

Thaker, M., C. R. Gabor, and J. E. Fries. 2006. Sensory cues for conspecific associations in aquatic San Marcos salamanders. Herpetologica 62:151-155.

Tupa, D. D., and W. L. Davis. 1976. Population dynamics of the San Marcos salamander, *Eurycea nana* Bishop. Texas Journal of Science 27:179-195.

Wetzel, R. G., and G. E. Likens. 1991. Limnological Analysis, 2nd ed. New York: Springer.

Wilson, W. D., J. T. Hutchinson, and K. G. Ostrand. 2017. Genetic diversity assessment of in situ and ex situ Texas wild rice (*Zizania texana*) populations, an endangered plant. Aquatic Botany 136:212–219.

Xu, X., C. Walters, M. F. Antoin, M. L. Alexander, S. Lutz, S. Ge, and J. Wen. 2010. Phylogeny and biogeography of the eastern Asian–North American disjunct wild-rice genus (*Zizania L., Poaceae*). Molecular Phylogenetics and Evolution 55(3):1008-1017.

Xu, X.-W., J.-W. Wu, M.-X. Qi, Q.-X. Lu, P. F. Lee, S. Lutz, S. Ge, and J. Wen. 2015. Comparative phylogeography of the wild rice genus *Zizania* (*Poaceae*) in Eastern Asia and North America. American Journal of Botany 102(2):239–247.

Young, F. N., and G. Longley. 1976. A new subterranean aquatic beetle from Texas (Coleoptera: Dytiscidae-Hydroporinae). Annals of the Entomological Society of America 69:787-792.

# 3

# Will the Biological Objectives Meet the Biological Goals?

This chapter addresses the first part of the Committee's statement of task, that is, whether the biological objectives can meet the biological goals for the listed species in the Edwards Aquifer system. As discussed previously, the biological objectives are different for each species, although they generally have three components: flow, water quality, and habitat. This chapter addresses whether the combined effects of the flow objective, the water quality objective, and the habitat objective achieve the biological goals for the fountain darter, Texas wild rice, the Comal Springs riffle beetle (CSRB), and the San Marcos salamander.

The Habitat Conservation Plan (HCP) contains a flow objective for each species that differs between the two systems. For the Comal system, the flow objective is to maintain a long-term average total discharge (50 years including the Drought of Record) above 225 cubic feet per second (cfs) with a minimum of 30 cfs that is not to exceed six months in duration, followed by at least 80 cfs for three months. For the San Marcos system, the flow objective is to maintain a long-term average total discharge above 140 cfs with a minimum of 45 cfs that is not to exceed six months in duration, followed by at least 80 cfs for three months. The water quality objective is the same in both systems: daily average water quality cannot deviate by more than 10 percent from historically recorded water quality conditions (long-term average) within the Edwards Aquifer. The conditions are measured at the spring openings for species that dwell near or in the springs (e.g., the CSRB) and in the river systems for the other species (e.g., the fountain darter). Texas wild rice and the San Marcos salamander do not have a water quality objective. Finally, it should be noted that the fountain darter has a more detailed water quality objective than the other species, which is that instantaneous water temperature must be maintained below 25°C and instantaneous dissolved oxygen (DO) maintained above 4 mg/L. The habitat objective varies by species and in some cases is worded similarly to a minimization and mitigation (M&M) measure.

## UNDERSTANDING THE RATINGS

The statement of task specified that, to the extent possible, the Committee should determine the likelihood that the biological objectives will achieve the biological goals. The Committee developed a rubric of four possible ratings: **highly likely, likely, somewhat likely,** and **unlikely**. The rating **highly likely** corresponds to minimal or no concerns about achieving biological goals, **likely** implies that the objective is expected to achieve biological goals, **somewhat likely** implies that the objective may reach the goals but there are significant concerns, and an **unlikely** rating is given where the objective is not expected to reach biological goals. Because the effort to determine the ratings was spread among Committee members with expertise in different species, an extensive discussion occurred to ensure consistency of ratings across the species. The ratings were based on the collective and consensus opinion of the Committee using the available evidence on *how the collection of objectives for a species would achieve the biological goals for that species*. The Committee did not parse the likelihoods in any further detail (e.g., whether a specific objective will achieve a specific goal) than a single overall determination per species.

Several assumptions about the ratings require explanation. First, the likelihood rating is specifically about whether the *objectives will meet the biological goals in the HCP* and is not a judgment about the likelihood of success of the restoration actions under way or planned or the effectiveness of other management actions. Second, the rating refers to the likelihood of success over the lifetime of the HCP, and not the annual probability of success. Third, there are two drivers that move determinations down from the highest rating of success (highly likely) and up (to higher success) away from the lowest rating of success (unlikely). One driver is the inferences possible from the available information, data, and past performance. The other driver results from lack of information or uncertainty in how objectives will achieve goals and from unknown future conditions.

The language is nuanced because the discussion becomes how much certainty is associated with the likelihoods, which are already in the form of probability statements. For example, there is extensive information on fountain darters and Texas wild rice, and so the determinations are offered with a relatively high degree of confidence. In contrast, for the CSRB and the San Marcos salamander, much less is known, which prevents determinations of the more definitive likelihoods (highly likely and unlikely) and pushes the determination to middle probabilities. Thus, to say "highly likely" or "unlikely" requires a higher degree of certainty.

For each species the determinations of the Committee are stated first, followed by the evidence and reasoning that led to the determination. Finally, the actions that could be taken to move the determination for a species up to a higher rating are discussed.

## FOUNTAIN DARTER

The biological goals for the fountain darter are to maintain specific areal amounts of various types of submersed aquatic vegetation (SAV) in several river reaches (the long-term biological goal, or LTBG, reaches) and to maintain specific fountain darter densities (number/area) in each SAV type. The biological objectives are (1) to meet certain minimum flow requirements in the Comal or San Marcos systems, (2) to maintain surface water quality within 10 percent of historical conditions for many parameters at various locations (except for DO and temperature; see above), and (3) to restore native SAV.

### Determination and Information Used

Will the biological objectives for the fountain darter achieve the biological goals? The Committee determined that, based on the available information, it is **likely** that the biological objectives will meet the biological goals for the fountain darter. The determination of likely is offered with a high level of confidence because it is based on evidence rather than based on a lack of information causing uncertainty to drive down the determination. The fountain darter differs from some of the other organisms of interest because it is well studied in the two systems, and extensive data and models (suitability, population dynamics) are available. (There is also a large body of available information for Texas wild rice.)

The Committee used many documents available from the Edwards Aquifer Authority (EAA). Some of the key sources were the recent SAV report (BIO-WEST and Watershed Systems Group, 2016), including the creation of the restoration reaches, inclusion of Texas wild rice as fountain darter habitat, discussion of the Texas wild rice expansion, and the time schedule of future restoration. The HCP (EARIP, 2012), Hardy (2009), Hardy et al. (2010), and Variable Flow Study reports (BIO-WEST, 2007) were consulted for the rationales and derivation of the biological objectives. The report that documented the development and preliminary simulations of the fountain darter population model highlighted known information and critical unknowns (Grant et al., 2017). In addition, the Committee relied on the many informative presentations made by EAA staff during Committee meetings, and the Committee did some simple analyses of the data.

### Evidence That the Objectives Are Achieving the Goals

Given that fountain darters are highly associated with SAV (see Figure 2-2), that flows are a major driver of local conditions (water velocities, depths, health of the SAV), and that fountain darters need relatively stable water quality conditions, the use of the three components (habitat, flow, and water quality) of the biological objectives makes good ecological sense. In addition, the goals and objectives were derived, in a logical manner, from empirical data available at the time of the HCP. The flow objectives were derived from habitat suitability modeling of each system. Habitat suitability modeling is an accepted method for determining minimum flows that support fish habitat, often used as part of Instream Flow Incremental Methodology in the licensing of hydropower facilities whose operations affect flows (Tharme, 2003; Lamb et al., 2004; NRC, 2015).

Evidence that the habitat, flow, and water quality objectives can meet the goals for fountain darters can be gleaned from past performance. This is the argument that the objectives have been successful to date, and so they would be expected to be successful into the future. EAA has been able to remove nonnative SAV and successfully plant native SAV in the LTBG reaches. For example, 3,595 $m^2$ of invasive plants were removed from the San Marcos system in 2017, out of a total target vegetated area in the San Marcos of 6,200 $m^2$ (Blanton and Associates, 2018). Nonnative SAV removal is obviously contributing to a substantial proportion of needed area available for active planting of native SAV, which in 2017 totaled almost 46,000 individual plants. Furthermore, during the last 15 years the average fountain darter densities in key SAV types have not shown persistent downward trends (Figure 3-1).

Although the scientific basis of the water quality component (i.e., 10 percent deviation, minimum DO, maximum temperature) is not well documented (as discussed in the last section of this chapter), the available data show that good water quality conditions have been generally maintained. Figure 3-2 shows a wide range in ambient daytime DO with highest densities of fountain darters between ~ 6 and 9 mg/L but certainly reasonable densities down to about 5 mg/L. The mean fountain darter abundance is 19.7 individuals/trap (median density = 10; 25th, 75th = 4, 24, respectively). Figures 3-3 and 3-4 show that DO is under 4 mg/L at most 2.5 percent of the time, and that temperatures over 25°C are observed only 2.5 percent of the time. Furl (2017) showed that conductivity and pH are frequently outside the 10 percent bounds, and yet the density goals for fountain darters are being met. The water quality component can be viewed as necessary

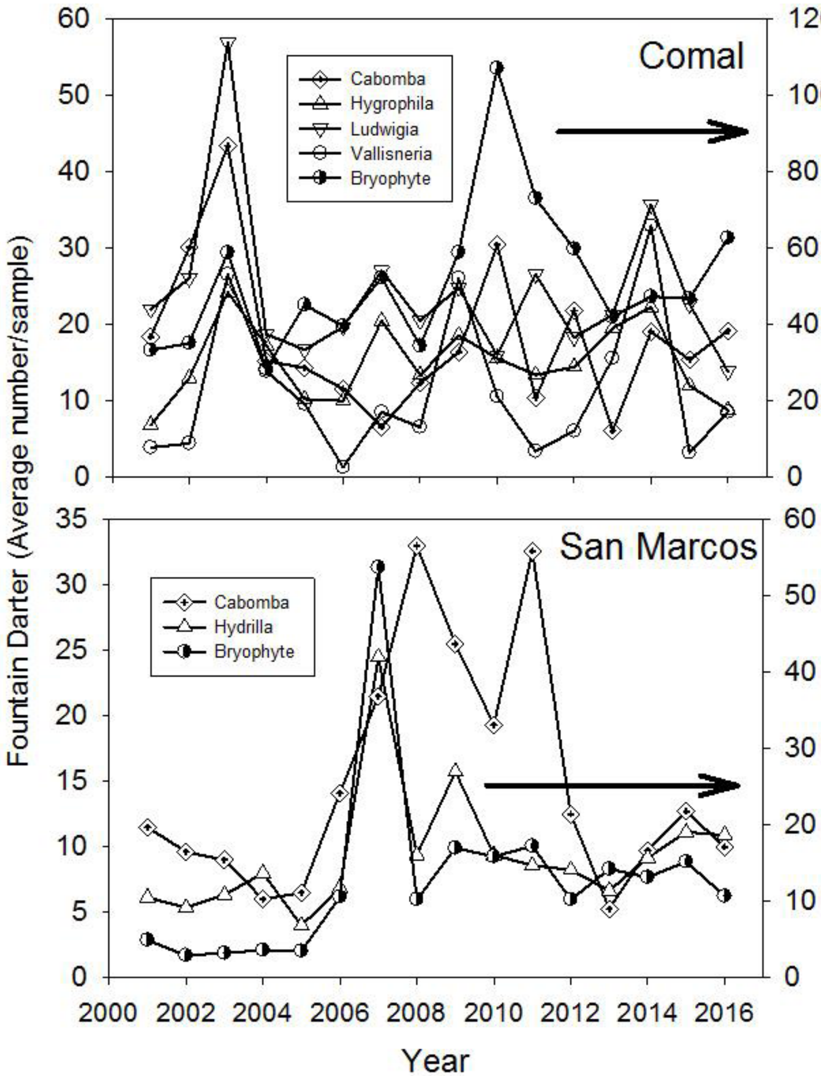



FIGURE 3-1 Average fountain darter densities by submerged aquatic vegetation type for each year in the Comal (top) and San Marcos (bottom) systems. The data are from EAA biomonitoring using the drop-net method for sampling fountain darters. Only SAV types with at least three to four measurements per year per SAV type and measurements spanning roughly April to November were included. The right-hand *y*-axis applies to bryophytes in the top panel and to *Hydrilla* in the bottom panel. SOURCE: Committee manipulation of Edwards Aquifer Authority data.

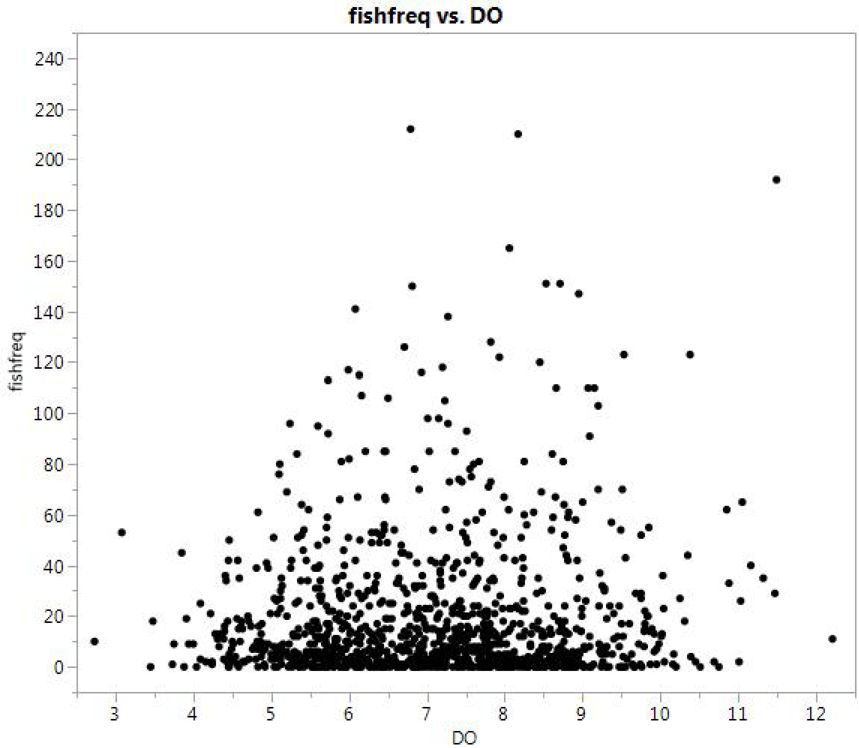



FIGURE 3-2 Abundance of fountain darters, captured in 2-m$^2$ drop nets, plotted against the ambient dissolved oxygen (DO) in mg/L at time of sampling. SOURCE: Committee manipulation of Edwards Aquifer Authority data.

but not sufficient; good water quality is needed but alone would not likely result in increased fountain darter abundance.

Recently, the EAA used the nonstandard optional adaptive management process to adjust their restoration activities related to the fountain darter. This is noteworthy for two reasons. First, it shows that the adaptive management process is a viable mechanism for changing the restoration in response to new information. This adds a degree of flexibility and robustness and thereby increases our confidence that the objectives can be effectively and efficiently modified to ensure that the goals are met in the future. Second, a solution was identified that addressed the immediate issues that arose that would have prevented the goals from being met. The solution was to add reaches (i.e., restoration reaches) so that habitat created

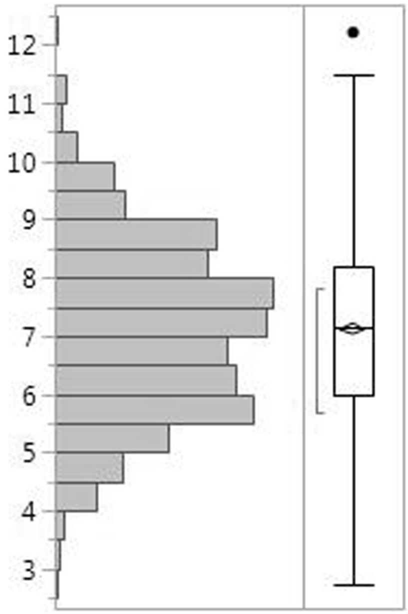



FIGURE 3-3 Range of dissolved oxygen (DO) observed during the drop-net sampling. This shows that DO is less than 4 mg/L at most 2.5 percent of time. *N* = 965. No nighttime data are available. SOURCE: Committee manipulation of Edwards Aquifer Authority data.

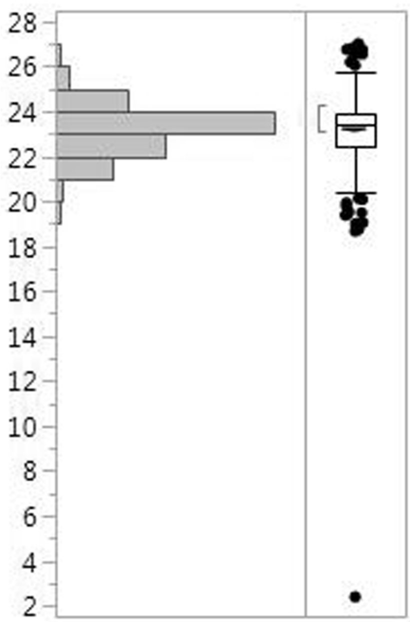



FIGURE 3-4 Range of temperature observed during the drop-net sampling. A temperature over 25°C is observed only 2.5 percent of the time. *N* = 965. Note that there is clearly an error in the dataset: the point indicating a water temperature of 2.4°C. SOURCE: Committee manipulation of Edwards Aquifer Authority data.

in these new reaches would contribute to the target number of fountain darters required (which is unchanged). In addition, Texas wild rice is now being credited as fountain darter habitat. These actions demonstrate that adaptive management, which always sounds good on paper, can actually be successfully used in practice by the EAA. Such management actions have been challenging to implement in other systems undergoing restoration, so this demonstration that the adaptive management process is working is noteworthy and adds reassurance that the objectives can achieve the goals in the future.

Another piece of evidence that the objectives can meet the goals was maintenance of general habitat conditions and achievement of the flow objective during the recent drought and flood years (2013–2014 and 2015). While there were reach-specific responses to these events (e.g., in the Old Channel), there were no systemwide massive losses of habitat (see Blanton and Associates, 2018, App. K2, Fig. 18) nor did EAA report any obvious sharp changes in fountain darter densities by SAV type. While achieving the objectives is a question of the effectiveness of the M&M measures, it is relevant here because the flow objective is described in the HCP as addressing uncertainty issues related to the habitat objective. If the flow objective had not been met under the recent extreme conditions, then this would leave the habitat objective more vulnerable to not meeting the goals.

Finally, as discussed above, there do not seem to be any obvious temporal trends in fountain darter densities by SAV type (Figure 3-1). Detection of persistent declines would suggest that the population was decreasing or that the additional habitat was simply diluting the fountain darter in its habitat rather than causing an increase in fountain darter population abundance. Some caution is needed because of the possibility of false negatives (i.e., low power prevents detection when a trend is occurring). Further analysis on the ability to detect events and trends in the fountain darter monitoring data (i.e., power analysis—see Green, 1989; Fairweather, 1991) would enable a determination of what magnitude of trends is detectable and shed some light on the likelihood of false negatives.

### *Notable Concerns*

**Habitat Objectives.** The recent addition of the restoration reaches raises some concerns about the capacity of the two systems for further adaptation. It is clear that the LTBG reaches in both systems have finite capacity for desired SAV. At some point, the systems will run out of options for good habitat reaches, which may affect the ability of the objectives to achieve the goals. The two systems are relatively small in size and have other activities occurring (e.g., recreation), and so there is a finite capacity for restoring good habitat reaches in both systems.

Achieving the biological goals of numbers of fountain darters (square meters times density) relies on the philosophy common in habitat restoration that habitat is limiting the population of interest. Otherwise, the new habitat simply results in a spatial redistribution of existing fountain darters. This is a very common debate in other systems, often referred to as "production versus attraction" (Grossman et al., 1997; Osenberg et al., 2002). Even under the best conditions of the habitat being the bottleneck, one should not assume that the responses will be proportional; that is, a 50 percent increase in habitat would not be expected to cause a 50 percent increase in the total population. It depends on how habitat affects growth, mortality, and reproduction over the fountain darter's life cycle. A sign that habitat is not limiting the fountain darter population would be decreasing median densities in some reaches as individuals move to a new habitat (i.e., become diluted).

Colonization of new habitat is based on dispersal and connectivity. The Comal and San Marcos systems are relatively small and linear in arrangement, and so connectivity is likely high and thus there is the potential (pathways available) for individuals to find the new habitat. However, EAA studies have shown that fountain darters are highly localized in their movement patterns and show relatively little net displacement over the order of days to weeks (BIO-WEST, 2014; Grant et al., 2017). This confined home range can limit individuals in finding new habitats. Whether dispersal becomes more limiting as less preferred (and maybe less connected) habitats are added remains a question. Data can be analyzed from the monitoring program to show that dispersal is not a limiting factor to fountain darters inhabiting new habitats.

Habitat stability is at risk from extreme events (droughts, floods) and other resets, such as dam repairs, changes in recreational access, possible plant diseases, and invasive species. As SAV restoration is anticipated to take until 2027, it is possible that some of these events may occur over the next nine years. These risks are recognized by the EAA (BIO-WEST and Watershed Systems Group, 2016). There is also the possibility of unanticipated effects in the future. For example, during development of the HCP, it was not anticipated that Texas wild rice would expand as it did, nor was it considered habitat in the calculations of fountain darter abundance. Despite these risks, the responses of SAV to the recent drought and floods are encouraging and support a high degree of stability.

A final caution is warranted because of the method used to compute median fountain darter densities to show compliance with the biological goals. The EAA uses cumulative median densities of fountain darter, which are very insensitive to any year-to-year changes (see Box 2-1).

**Flow Objectives.** The flow objectives were designed, in part, to protect against uncertainty in how the habitat objective would perform. The flow objectives were derived from habitat suitability index (HSI) modeling. However, the analyses were done almost 10 years ago and the systems have changed since then, so some of the interpretations of the results should be confirmed. Although HSI modeling is widely used, it is often criticized for several of its key assumptions (Mathur et al., 1985; Gore, 1989; Railsback, 2016). A major assumption is that actual species abundance will track how habitat quality and quantity vary in space and time. HSI results are best interpreted as *the capacity or potential* for abundance, rather than how the population abundance will respond.

The HSI analyses used to derive the flow objectives included some questionable methodological decisions. First, simulations were steady-state flows, and so temporal variation in flows was not directly assessed. Given the small size of the two systems, inferring how dynamically varying flows affect fountain darter habitat by piecing together results from steady-state flows is reasonable for average conditions but less robust for extreme low and high flows. Third, the HSI modeling for the fountain darter was correlated with velocity, depth, and vegetation type. The vegetation maps were assumed invariant under all conditions, including velocity, depth, and temperature, which is reasonable for short-term predictions but more questionable over multiple years when vegetation responds to changing flows. Furthermore, the specific suitability relationships can be refined based on new data and statistical fitting methods (e.g., Ahmadi-Nedushan et al., 2006). The Committee mentions these issues for completeness and does not consider any to be of critical importance to the determination of **likely**. The use of older data could be addressed by revisiting the HSI analyses, as suggested in NRC (2015).

**Water Quality Objectives.** The water quality objectives help to create a stable environment needed by the fountain darter, but one could question some aspects of the DO and temperature objectives. DO is measured during the daytime; nighttime values would be lower. For both DO and temperature, the use of minimum DO and maximum temperature are reasonable, but some caution arises when the long term (decades) is considered because of warming trends. The biological basis for the objectives, especially the 10 percent deviations, should be confirmed using empirical data.

### Conclusion and Actions Needed to Improve the Rating

The evidence in support of the biological objectives meeting the biological goals is based on empirical observations and the cumulative input (including the development of the HCP) from many experts and stakeholders.

Examination of past performance showed successful removals and planting of SAV, no obvious drops in fountain darter densities, stable water quality, and a successful adaptive management action demonstrating flexibility in the process. The cautionary evidence is mostly related to the use of older information in the HSI modeling, lack of certain analyses that would increase confidence (described below), and uncertainty about future options to expand restoration in new reaches and how the systems and fountain darters will respond to future conditions. In the case of fountain darters, substantial data and information from monitoring, process studies in the field and lab, and modeling have led to a conclusion about the likelihood of success that is offered with relatively high confidence.

There are several actions the EAA could take to move the determination of **likely** toward **very likely**. First, the EAA can show that flows and habitat conditions during the Variable Flow Study are reasonable for today and into the future. The study was done almost 10 years ago, and the conditions in both systems have changed and both systems have experienced extreme events. Second, update the HSI modeling to reflect the current state of the systems and to explore scenarios such as the Drought of Record and flooding. Third, expand fountain darter monitoring to the restoration reaches to confirm that target densities are being met. Fourth, analyze the fountain darter data for temporal trends in population abundances that reflect each year and only each year. Presentations to date of fountain darter abundance time series have used either monitoring data that may not be quantitative enough (the dip-net data) or quantitative data (drop-net data) that show only cumulative median fountain darter densities. In addition, a power analysis on the abundance time series could help guide the interpretation of false negatives (no detection of downward trend when there is actually a decrease).

## TEXAS WILD RICE

The long-term biological goals for Texas wild rice were determined by (1) an evaluation of the maximum occupied area of Texas wild rice that has been present in the San Marcos River in each segment over time, (2) analysis of the physical habitat modeling carried out by Hardy (2009) and Hardy et al. (2010), and (3) the 1996 FWS recovery plan goals (FWS, 1996). The biological goals for Texas wild rice are to maintain a range of areal coverage in four reaches of the San Marcos River and to maintain a range of percentages of the coverage in a given reach (see Table 2-2 for details). The biological objectives are (1) to meet certain minimum flow requirements in the San Marcos system, (2) to maintain minimum areal coverage in the four river reaches during the Drought of Record, and (3) recreation awareness, with control in high-quality habitat areas when flow is below 100 cfs.

### Determination and Information Used

The Committee determined that, based on available data, it is **likely** that the biological objectives will be able to meet the biological goals for Texas wild rice in the San Marcos River. This determination was based partially on information the Committee garnered from the impressive amount of available data as well as from oral presentations by EAA staff, discussions of existing conditions and M&M measures implemented in the river by City of San Marcos staff, and site visits to the river. In addition, relevant scientific literature was consulted, along with a voluminous collection of regulatory documents and raw data. This information has provided a historical review of Texas wild rice distribution in the San Marcos River from the time of its initial scientific description in 1933 (confirming it as a unique new species) through the 2017 HCP Annual Report (Blanton and Associates, 2018).

### Evidence That the Objectives Are Achieving the Goals

The most persuasive evidence that the objectives will be able to meet the long-term goals is the gain in Texas wild rice coverage in recent years (Table 3-1). The recent SAV report (BIO-WEST and Watershed Systems Group, 2016), as well as the most recent HCP Annual Report (Blanton and Associates, 2018) give strong evidence that many of the measures that have been taken in the San Marcos basin are working. This suggests increased resilience in this ecosystem, which was once in precarious condition. The only exception is downstream of I-35 in 2017, where there may be water quality issues (addressed below). The gain in Texas wild rice coverage comes despite a near record drought in 2013–2014 as well as recent flooding. Although not every section of the San Marcos River saw a spectacular resurgence of Texas wild rice, some areas, such as the City Park reach and Spring Lake, were remarkable, with the coverage of Texas wild rice increasing threefold in a single year. This bodes well for achievement of the long-term goals in future years, and it is the foremost reason that it was decided that they were likely to be met by 2027.

#### *Notable Concerns*

**Flow Objective.** The flow objective for Texas wild rice was designed to protect against an extended period of drought. The origins of the flow objective include Hardy (2009), who constructed a detailed grid to represent

TABLE 3-1 Texas Wild Rice 2016 and 2017 Areal Coverage, Change in Areal Coverage 2013–2017, and Change in Areal Coverage 2016–2017, per Long-term Biological Goal and Restoration Reach

| | **Total Area ($m^2$)** | | | |
|---|---|---|---|---|
| | | | **Change** | |
| **Reach** | *2016* | *2017* | *2013–2017* | *2016–2017* |
| Spring Lake | 47.1 | 184.1 | 184.1 | 137.0 |
| Spring Lake Dam | 887.3 | 1,389.3 | 1,190.8 | 502.0 |
| Sewell Park | 1,185.8 | 1,811[a] | 1,144.7 | 625.2 |
| Below Sewell to City Park | 2,429.0 | 2,810[a] | 1,598.0 | 381.0 |
| City Park | 1,561.5 | 2,247.0 | 1,863.0 | 685.5 |
| Hopkins Street to Snake Island | — | 1,168.57[a] | — | — |
| Cypress Island to Rio Vista Dam | 238.0 | 246.9 | 246.9 | 8.9 |
| I-35 (upper and lower) | 276.0 | 512.1 | 512.1 | 236.1 |
| Below I-35 | — | 55.61[a] | — | — |

[a]BIO-WEST data mapped July 2017.
SOURCE: Blanton and Associates (2018).

the factors that can affect Texas wild rice habitat, as part of an effort to conduct a habitat suitability analysis. Hardy (2009) ended up using only two parameters to assess the physical habitat: water depth and velocity. Using these two parameters, Hardy calculated the habitat suitability for a range of San Marcos River discharges. This exercise revealed that the optimal discharge was around 135 cfs, with declines in habitat suitability on either side of this discharge. Although avoiding explicit suggestion of what flow rate should be adopted to sustain Texas wild rice during droughts, Hardy (2009) did caution that a flow rate of 30 cfs is a concern. Hardy et al. (2010) updated the habitat suitability analysis for Texas wild rice, again using only water depth and velocity as the primary parameters. As for the fountain darters, the habitat suitability modeling may be out of date now because it was completed almost 10 years ago and the systems have changed.

**Water Quality Objective.** For unknown reasons, there was no term in the existing habitat suitability model that Hardy (2009) developed for Texas wild rice to assess water quality issues. This is somewhat surprising since temperature was part of the fountain darter habitat suitability modeling. The sensitivity of $C_3$ plants to high temperatures in aquatic environments was mentioned briefly in Hardy (2009), and he was likely aware of its overall importance. The realization that there are multiple modes of photosynthesis (first mentioned in the scientific literature by Hatch and Slack, 1966) has been increasingly used to explain differences in stress responses in a variety of higher plant groups over the last several decades (Ehleringer et al., 1997; Sage, 2004; Christin and Osbourne, 2014). Chapter 2 briefly outlined the problems that aquatic plants experience in accessing $CO_2$ when they are exposed to prolonged temperatures exceeding 25°C if their primary photosynthetic mechanism is $C_3$ rather than $C_4$. Temperature stress has two important effects on $C_3$ species (including Texas wild rice). The first effect is an internal decline in plant growth, and the second is that nonnative $C_4$ species are not affected and can easily outcompete them—especially in a karst environment (Wang et al., 2017). During average- and high-flow years, the spring waters emanating from the Edwards Aquifer have ample cooling capacity. However, during droughts and if water temperature rises, Texas wild rice photosynthesis will slow considerably. The invasive weedy $C_4$ species, such as *Hydrilla,* will then accelerate their uptake of $CO_2$ and eventually drive pH up to 8 or beyond. In this pH range, $C_4$ species can rely on bicarbonate as their prime carbon substrate, whereas $C_3$ species cannot (Spence and Maberly, 1985). The latter first become carbon limited and ultimately carbon starved as pH climbs to 8 and beyond. Thus, without temperature being among the biological objectives, the HCP may lack an important driver that could limit Texas wild rice growth under stress conditions whenever severe droughts occur in the San Marcos system.

**Habitat Objective.** The main habitat objective is recreation awareness, with control in high-quality habitat areas when flow is below 100 cfs. Despite the high level of recreation in the San Marcos River, there has been a very thoughtful approach in addressing the various impacts of recreation in this system. The Committee was particularly impressed by the incorporation of SCUBA diving for students at Spring Lake with the objective in assisting with the aquatic gardening annually.

The recent decision to remove nonnative SAV species from the system should have a positive effect on Texas wild rice populations by reducing competition of very aggressive species that can take up carbon when pH exceeds 7.5. Field plots should be used to confirm this, by means of a Before-After-Control-Impact (BACI) experimental design and/or a mesocosm approach with water from the San Marcos River (Smith et al., 1993). Along with these positive developments is the recent approval (using the adaptive management process) to count Texas wild rice coverage as fountain darter habitat in the San Marcos River, thereby eliminating a source of conflict in the goals of the HCP. This should eliminate the situation where Texas wild rice was essentially pitted against the other SAV species in terms of coverage.

### Conclusion and Actions Needed to Improve the Rating

The evidence in support of the rating is based on empirical observations of Texas wild rice coverage gain, even in the face of recent floods and droughts. In addition, the decision to remove nonnative SAV has a long-term benefit for Texas wild rice because it will lessen the risks that nonnative SAV species will be more competitive when pH is higher than 8 in this system. Finally, adaptive management has led to now including Texas wild rice as fountain darter habitat. The cautionary evidence is related to the absence of a defined water quality objective. As with the fountain darter, monitoring and successful restoration of Texas wild rice to date have led to a conclusion offered with relatively high confidence.

The main action that the EAA could take to move the determination of **likely** toward **very likely** would be to create a water quality objective for Texas wild rice, especially during low-flow conditions. If a water quality objective were to be created for Texas wild rice, an upper value for temperature in the San Marcos River could be chosen by local experts after consulting the existing scientific literature. A good starting point for initial discussions might be 25°C. Also, it will be important to continue to remove nonnative SAV, and there may be value in making this a stated biological objective for Texas wild rice. Note that temperature becomes less important once nonnatives have been removed from the system.

## COMAL SPRINGS RIFFLE BEETLE

The biological goals for the CSRB are to maintain specific beetle density (number/lure) in three locations (Spring Run 3, the western shoreline of Landa Lake, and the Spring Island area) and to maintain silt-free gravel and cobble substrate in the same three locations. The biological objectives are (1) to meet certain minimum flow requirements in the Comal system, (2) to maintain spring water quality within 10 percent of historical conditions at the three locations, and (3) to restore riparian habitat adjacent to spring openings at Spring 3 and the western shoreline to reduce siltation.

### Determination and Information Used

The Committee determined that, based on the available information, it is **somewhat likely** that the biological objectives will meet the biological goals for the CSRB. This determination was based on the fact that there are substantial needs for additional information related to quantitative monitoring of CSRB populations. Furthermore, mechanisms to evaluate the efficacy of riparian restoration in eliminating silt at spring openings are limited and not currently in place. Finally, there is some question about the validity of the flow objective for two of the reaches in the Comal system that are monitored to determine compliance with the CSRB biological goals.

To reach their determination, the Committee made use of biomonitoring data for the CSRB and reviewed evidence that riparian restoration activities are working. It considered how well the flow objective reflects the habitat suitability modeling done for the CSRB as found in Hardy (2009) and Hardy et al. (2010). And it reviewed Appendix D from the HCP (EARIP, 2012), the Variable Flow Study reports (BIO-WEST, 2007), and numerous reports on the CSRB from the Applied Research Program (see Table 5-3 in NASEM, 2017).

### Evidence That the Objectives Are Achieving the Goals

Chapter 2 discussed the limitations of quantitative sampling of the CSRB, in terms of the enormous variation in the number of samples collected each year, as well as the lack of a standard protocol for sampling until very recently. Given these sampling limitations and the high number of zero samples recorded, it is not surprising that the biomonitoring data show no particular trends over the last 12 years (Figure 3-5). Hence, unlike

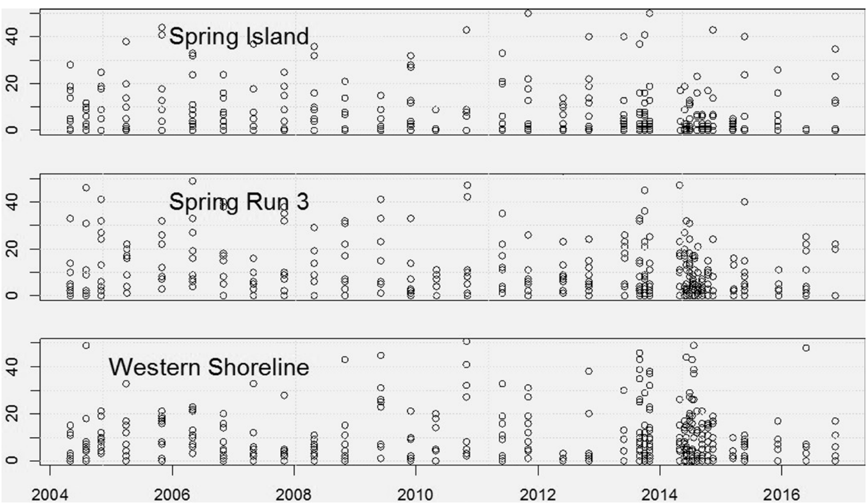



FIGURE 3-5 Biomonitoring data for Comal Springs riffle beetle from all three long-term biological goal reaches, 2004–2016. The *y*-axis is number of beetles per lure, with a maximum value of 50, such that not all data are shown. SOURCE: Furl (2017).

with Texas wild rice, the monitoring data do not provide evidence that the objectives can meet the biological goals for the CSRB.

### *Notable Concerns*

**Flow Objective.** The flow objective for the CSRB is the same as for the fountain darter. The flow objective was developed to sustain flow sufficient to maintain habitat, and therefore populations of the listed species, which in the case of the Comal system are the fountain darter and the CSRB. The habitat suitability modeling done for the fountain darter played a significant role in determining the flow objectives in the Comal system; hence, the criticism of that HSI modeling discussed previously (see Fountain Darter section) is also applicable here. Nonetheless, it is also important to consider the extent to which the flow objectives take into consideration the habitat suitability modeling done for the CSRB.

As discussed in Appendix D of the HCP (EARIP, 2012), the habitat suitability modeling for the CSRB was done at three major springs in the Comal system (Spring Runs 1, 2, and 3). Habitat suitability for the CSRB was modeled to be a function of surface water depth and velocity, with the optimal water depth ranging from 0.02 to 2.0 feet and velocities up to 2 feet per second (Hardy, 2009). Hardy (2009) estimated a 30 percent reduction in CSRB habitat for Spring Run 1 at flows < 150 cfs, while the other runs would not experience a loss in estimated habitat until flows were < 125 cfs (Figure 3-6). There was no estimated suitable CSRB habitat at flow rates less than 30, 65, and 100 cfs for Spring Runs 1, 2 and 3, respectively. However, there are no data showing how different flow rates affect habitat suitability in the other two reaches used for LTBG monitoring (western shoreline of Landa Lake and Spring Island area).

Other assumptions went into establishing the Comal flow objectives, including the historical evidence of the CSRB surviving the Drought of Record when all major spring runs ceased to flow for five months. It is assumed that repopulation of the major spring runs came from emigration of the CSRB from smaller springs in Landa Lake that remained wetted during the Drought of Record. Although only the LTBG reaches are used for assessing if CSRB biological objectives are being achieved, it has been estimated that approximately 50 percent of CSRB habitat exists in other areas of Landa Lake that are less likely to become dry at extreme low flows (e.g., < 30 cfs) (EARIP, 2012, App. D). This additional habitat is expected to act as a refugium and ultimately sources of the CSRB in cases of extended low, or zero, flow at the main springs. There is also the hypothetical potential for the CSRB to survive prolonged periods of drought by retreating into spring openings and relying on subsurface habitats.

According to Hardy (2009), a minimum of 30-cfs spring flow would

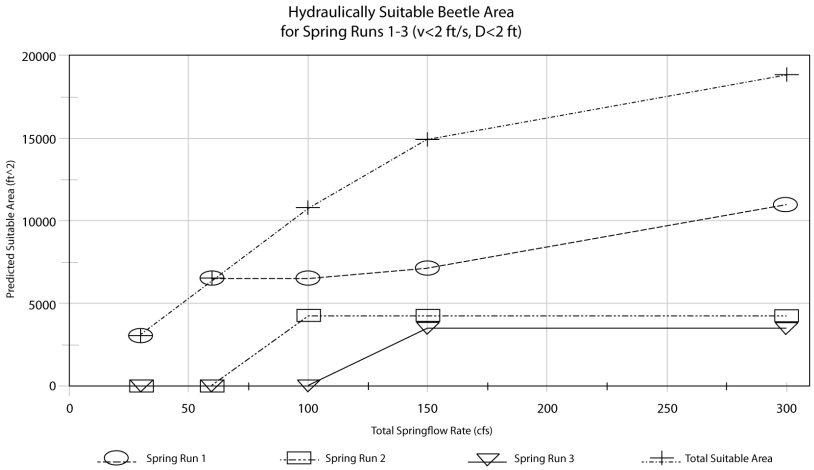



FIGURE 3-6 Simulated suitable habitat for the Comal Springs riffle beetle in three Comal Spring runs at various spring flow rates. SOURCES: EARIP (2012, App. D) and Hardy (2009).

only provide suitable CSRB habitat at Spring 1, with no habitat available at the other two main springs. Indeed, at 100 cfs and 60 cfs, CSRB habitat is eliminated in Spring 2 and Spring 3, respectively. So, while the long-term objective of 225 cfs is likely to achieve the biological goals of the CSRB, it is more difficult to determine if the minimum flow of 30 cfs not to exceed six months, followed by 80 cfs for three months, would be adequate. At flows less than 100 cfs, potential CSRB surface habitat is eliminated at Springs 2 and 3, and it is unknown how long these springs will remain dry if overall flow is further reduced for nine months. Based on this limited information, the 30 cfs minimum flow for six months followed by 80 cfs for three months may be appropriate to achieve the biological goals of the CSRB. This assessment is also dependent on how well the habitat suitability modeling actually predicts CSRB populations, an issue discussed earlier for the fountain darter.

There is an important disconnect between the habitats for which the habitat suitability modeling was done (Spring Runs 1, 2, and 3) and the habitats where CSRB populations are currently monitored for meeting the long-term biological goals (Spring Run 3, western shoreline of Landa Lake, and Spring Island area). The HSI model used to support the flow objectives for Comal has not been repeated for the western shoreline of Landa Lake and Spring Island. Furthermore, Figure 3-6 shows that suitable habitat in

Spring 3 is eliminated well above the 30-cfs minimum, suggesting that for at least one of the monitored locations the minimum flow objective is unlikely to achieve the biological goals. Additional studies are needed to validate the habitat suitability models of Hardy (2009) in the areas where CSRB populations are monitored, to better determine the likelihood of meeting the CSRB biological goals.

**Water Quality Objective.** The water quality objective is to maintain aquifer water quality from the spring openings within 10 percent of historical conditions in the three LTBG reaches. The known habitat of the CSRB is immediately within and adjacent to spring openings that receive continuous subterranean flow, the quality of which has not varied significantly over time. Thus, it could be argued that the water quality objective is not particularly relevant to meeting the biological goals for the CSRB. However, there are at least three distinct scenarios that could cause water quality of the springs to deviate by more than 10 percent. One would be a toxic chemical spill that enters the aquifer, thereby affecting spring water quality. The second would be a catastrophic riparian bank collapse that buries spring openings in the LTBG reaches. Although these two scenarios are unlikely to occur, they should be considered in long-term HCP planning. The third scenario that might cause spring water quality to deviate by more than 10 percent is chronic erosion from riparian areas sufficient to cover and bury spring openings with sediment in a way that changes temperature and DO conditions (this is discussed in greater detail in the Habitat Objective section below). Based on current water quality monitoring and laboratory studies, the temperature and oxygen values at the spring openings are rarely outside the tolerance thresholds for the CSRB (Nowlin et al., 2016; BIO-WEST, 2017). As discussed earlier for the fountain darter, the water quality objectives are necessary, but not sufficient, to ensure that the biological goals are met.

**Habitat Objective.** A riparian zone restoration program was implemented in 2013 to improve CSRB habitat in Spring Run 3 and the western shoreline. The restoration activities have been implemented each year with minor modifications annually to reduce fine-sediment accumulation. In 2016, the activities included removal and/or treatment of exotic vegetation and replanting the shoreline with native vegetation; the construction and maintenance of erosion structures to limit runoff; and sediment and vegetation monitoring. As discussed in greater detail in Chapter 4, while there is documented success of nonnative riparian plant removal, there is also substantial sediment capture by the erosion structures, calling into question the ability of this objective to meet the biological goal of silt-free substrate unless there is continuous maintenance of the erosion control structures.

Furthermore, there have been no quantitative assessments for measuring sedimentation at the CSRB spring openings, so it is difficult to assess how riparian restoration activities will affect CSRB biological goals.

### Conclusion and Actions Needed to Improve the Rating

There has been considerable recent research on the CSRB that has revealed important information on some life history traits using laboratory colonies and conditions, physiological tolerances to abiotic conditions such as temperature and oxygen, and habitat and trophic relationships with detritus from riparian buffers. In addition, the new standard operating procedure for the cotton-lure sampling method is an important step in improving the monitoring of CSRB populations. Although this surge in understanding of the basic natural history and biology of the CSRB is to be lauded, there remain informational needs that would increase the potential for the biological objectives to achieve the goals. Based on the limitations associated with (1) the lack of quantitative monitoring of CSRB populations, (2) determining whether riparian restoration can actually eliminate silt at spring openings, and (3) the lack of habitat suitability modeling in the LTBG reaches, collectively the biological objectives are **somewhat likely** to achieve the long-term biological goals of the CSRB.

The following actions could be taken to move the rating from **somewhat likely** to **likely**. First, as has been mentioned in previous reports of the Committee (NRC, 2015; NASEM, 2017) and in Chapter 2, improvements to the sampling of the CSRB are critical in order to better understand what the true beetle population is in the monitored reaches. Second, it is highly recommended that a plan be developed to quantitatively monitor CSRB habitat sedimentation associated with continuing riparian restoration efforts. Finally, if the habitat suitability modeling was repeated in the LTBG reaches, it would increase confidence in the ability of the flow objectives to meet those goals.

## SAN MARCOS SALAMANDER

The biological goals for the San Marcos salamander are to maintain specific salamander populations (number/m$^2$) in three locations (hotel site, riverbed site, and Spring Lake Dam site) and to maintain silt-free gravel and cobble substrate in the same three locations. Maintaining silt-free gravel is assumed to be crucial for ensuring suitable habitat for San Marcos salamanders, which use interstitial spaces within the gravel to seek refuge and forage. The biological objectives are (1) to meet certain minimum flow requirements in the San Marcos system that are the same as those for the fountain darter and Texas wild rice, (2) aquatic gardening at the riverbed and hotel sites, and (3) regulation of human recreation activity at the spillway site. The latter two are odd because as stated they are virtually identical to certain M&M measures. Note that there is no water quality component of the biological objective for San Marcos salamanders.

### Determination and Information Used

The Committee determined that, based on the available information, it is **somewhat likely** that the biological objectives will meet the biological goals for the San Marcos salamander. Like the CSRB, biological data that could provide evidence are lacking for this species. Much of the current scientific information on the species is based on observations and experiments with captive individuals. This lack of information precluded us from assigning a more definitive likelihood. Also, there is no stated water quality objective for the San Marcos salamander, although water quality is suspected to be an important factor in the long-term persistence of the species.

To reach this determination, the Committee considered the biomonitoring data for San Marcos salamanders; historical monitoring of the species (an interpretation of those results) within the San Marcos springs system and a short reach of the San Marcos River downstream from Spring Lake Dam spillway (Tupa and Davis, 1976; Nelson, 1993; FWS, 1996); progress to date implementing numerous recreation-associated M&M measures in Spring Lake and just below the dam spillway; and various reports already cited for the other species.

### Evidence for and Against the Objectives Achieving the Goals

Like the CSRB, evidence in the form of positive trends in abundance is not as easy to come by for San Marcos salamanders as it is for fountain darters and Texas wild rice. According to the HCP, both the habitat (extent of silt-free gravel) and population (minimum median salamander densities) biological goals "must be met concurrently to be deemed successful" (EARIP, 2012, pp. 4-34, 4-35). Unfortunately, determining if the goal of maintaining ≥ 90 percent silt-free gravel at each of the sampling reaches is being met is not possible; neither the HCP annual reports nor the biomonitoring reports present any data or summaries of the extent of silt-free gravel at the three reaches. Also conspicuously absent is any mention of the aquatic gardening efforts, though, according to the HCP, this management action is conducted quite frequently.

Assessing the population-based goal is more straightforward because annual estimates of salamander densities have been conducted continuously. On the basis of estimated densities of salamanders among the three sites through 2016, the EAA appears to be generally meeting its goals. Although density estimates at each of the sites vary considerably among sampling periods within and among years (some single estimates greatly exceed the targets and others fall well short of them), the measured density values during more than 15 years of consecutive sampling remain very close to the targets (Figure 3-7). However, with regard to salamander sampling, the 2017 annual biomonitoring report states "The estimates created from this work are valuable for comparing between trips, but any estimates of total population size derived from this work should be viewed with caution" (BIO-WEST, 2018). That is, there is no way to know if trends in salamander numbers over time within the three reaches are an indicator of true population trends.

**Flow Objective.** As it pertains to San Marcos salamanders, the flow objective will help to maintain the appropriate extent of silt-free gravel (≥ 90%) at the three sites where salamander monitoring occurs. In addition to supporting silt-free gravel, adequate spring flow also facilitates growth of SAV that provides food and shelter for San Marcos salamanders.

Unlike the situation with the fountain darter, HSI modeling was not conducted to assess potential impacts of spring flow variability on San Marcos salamanders. Nonetheless, San Marcos salamanders can retreat into subterranean refuges at spring vents during periods of extremely low spring flow, such as the Drought of Record (see Chapter 2 of this report). Given this feature of their natural history, and the fact that they are largely limited to Spring Lake, they are likely more resilient to reduced spring flow than fountain darters. Therefore, the flow objective for fountain darters should be adequate for San Marcos salamanders. As with fountain darters, protection and maintenance of salamander habitat in Spring Lake during excessively high-flow events is uncertain and needs to be considered.

**Habitat Objectives.** Regulation of recreation at the spillway site is one of the habitat objectives for the San Marcos salamander. Of all the listed species, San Marcos salamanders arguably are the least likely to be negatively impacted by recreation from spring and river users because of the salamander's limited extent. The species is primarily confined to Spring Lake, although some individuals (roughly half the densities observed at Spring Lake sites) are found in the very upper reach of the San Marcos River, to ~50 meters below the Spring Lake Dam spillway. Access to Spring Lake proper is highly regulated and managed, but people often access the river at the dam spillway. People currently are only allowed in Spring Lake to take SCUBA classes, view the lake from glass-bottom boats, and tour the lake on paddleboards, canoes, and kayaks. All human recreation in the lake is organized and managed by the Meadows Center for Water and the Environment operated by Texas State University. More important would

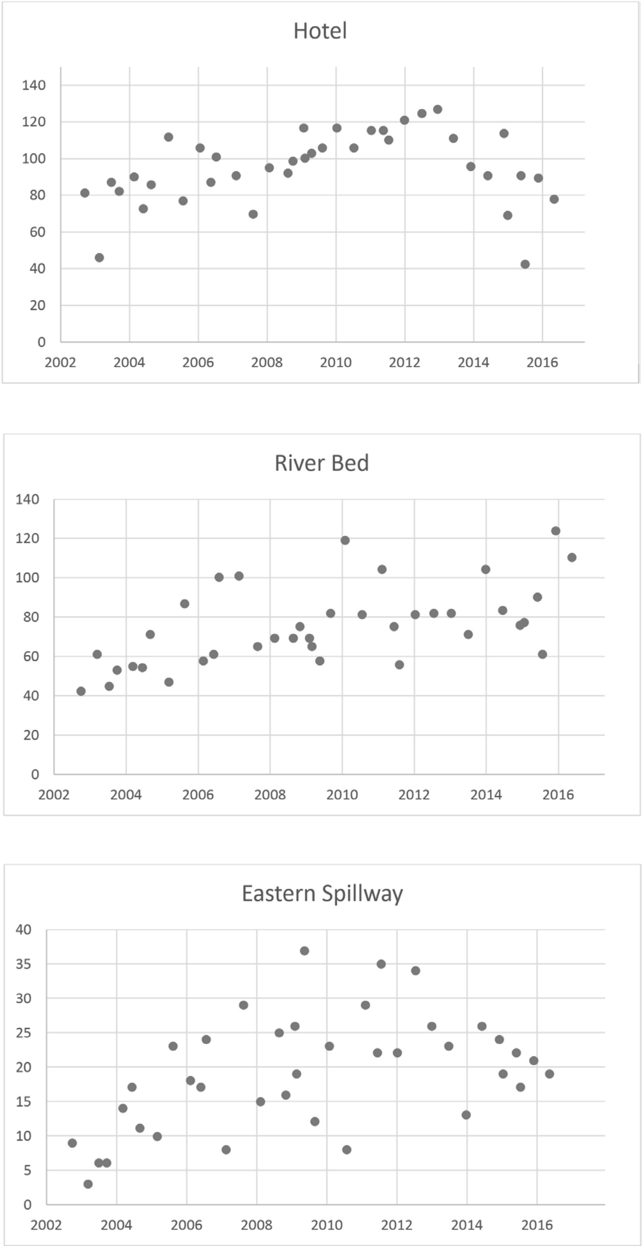



FIGURE 3-7 San Marcos salamander densities at the three long-term biological goal sampling sites, 2002–2016. The *y*-axis is number per square meter. SOURCE: Committee manipulation of Edwards Aquifer Authority data.

be to better regulate recreational access to the 50-meter reach of the San Marcos River just below Spring Lake Dam to eliminate bank erosion and direct disturbance of salamander habitat. Recreational impacts here are far greater than within Spring Lake. Restricting public access to this short section of the upper San Marcos River would curtail human-caused bank erosion and eliminate disturbance to rocks and other salamander habitat, which should facilitate the maintenance of silt-free gravel and possibly increase salamander densities.

The other habitat objective, called aquatic gardening, refers to the hand removal of algae and SAV around spring vents at the hotel area and riverbed area in Spring Lake. In addition to removing vegetation, trained divers will "fin the area around the springs to remove accumulated sediment." The process of aquatic gardening is important to meeting the biological goal of silt-free gravel.

Although it is not explicitly identified in the HCP as an objective, an implicit habitat objective for the San Marcos salamander is the management of riparian areas along a short stretch of the San Marcos River just downstream from Spring Lake Dam. Impacts of recreational use, which contributes to riverbank erosion and increased siltation, in this short section of the San Marcos River is greatest during periods of low flow. During high-flow conditions, water depth is greater and underwater hazards (e.g., remains of an old dam) discourage recreationist use. During low-flow conditions, the hazards are exposed and this leads to human use of the site. People access the river and physically disturb the location by moving rocks "to create structures, dams, underwater rock art, and artificial channels" (Blanton and Associates, 2018, App. D, Fig. 18). Such perturbation certainly has the potential to impact salamander habitat; thus, protection of this area via bank stabilization and exclusion of recreationists is an important measure at this site.

**Water Quality Objective.** A water quality objective is glaringly absent for the San Marcos salamander. Maintaining suitable water quality (e.g., temperature, DO, nutrients, and pesticide/herbicide residues) has been identified by numerous authors as essential for long-term persistence of San Marcos salamanders. Research has determined critical thermal maximum ($CT_{max}$) and oxygen consumption rates for the species (see Chapter 2), but nothing is known about effects of nutrients and environmental contaminants. Such studies should be considered as part of the Applied Research Program. Equally important is determining the effects of altered water quality on the invertebrate prey species upon which San Marcos salamanders depend. And, as noted for the CSRB, consideration of catastrophic events, such as a toxic chemical spill that enters the Edwards Aquifer, should be addressed in long-term HCP planning.

### Conclusion and Actions Needed to Improve the Rating

Considering the lack of detailed biological data for the San Marcos salamander in the peer-reviewed literature, historical estimates of population size, recent estimates of densities at the three sampling reaches, and lack of information on the effects of aquatic gardening and the extent of silt-free substrates, the Committee deems the biological objectives **somewhat likely** to achieve the long-term biological goals for San Marcos salamanders.

There are several actions the EAA could take to move this assessment to **likely**. The first is to develop a water quality objective for San Marcos salamanders, which should be informed by and concordant with water quality objectives for the other covered species. The second action is to better regulate recreational access to the 50-meter reach of the San Marcos River just below Spring Lake Dam to eliminate bank erosion and direct disturbance of salamander habitat. Third is to quantify, monitor, and report the extent and outcomes of aquatic gardening and maintenance of silt-free gravel at the salamander study-reaches. A final action would be to report on the variation associated with San Marcos salamander density estimates and augment the current sampling protocol with a new method to estimate proportion of area occupied and detection probability of San Marcos salamanders (see Chapter 2).

## WATER QUALITY COMPONENT OF THE BIOLOGICAL OBJECTIVE

Found in several places within the HCP is the objective for maintaining water quality within 10 percent of historical conditions. This objective is given for fountain darters in both the Comal and San Marcos systems and for the CSRB, Peck's Cave amphipod, Comal Springs dryopid beetle, and Texas blind salamander. In the case of the latter four organisms, the water quality under consideration is that of the aquifer water measured at the spring openings, while for the fountain darter the water being considered is the river water in both systems. Note that this water quality objective is actually the sole *biological goal* for the Texas blind salamander, the Comal Springs dryopid beetle, and the Peck's Cave amphipod because there are no population metrics that can be used for these organisms (given the difficulties with sampling these species).

The Water Quality Monitoring Work Group report (EAHCP, 2016) spends some time determining which datasets to use for setting historical levels, but it is insufficient in explaining why those levels (or divergences from those levels) actually matter. The report suggests that many of the criteria and thresholds are based on State Water Quality levels and are not necessarily tied to either the listed species or other important species, such as SAV. There is little description of how the 10 percent rule came to be applied to the fountain darter (or other taxa). Furthermore, the Committee could find no publication that actually lists all of the water quality parameters being considered and their historical values.

The water quality objective appears to be a conservative approach to identifying potential conditions of concern; it could be described as an early warning indicator of potential water quality issues. The objective was defined, however, without the benefit of historical data on the actual variations in water quality measures. As such, the objective should be recognized as an interim objective that should be informed and updated by the actual variations in water quality that occur that *do not lead to significant negative consequences for the listed species*. Admittedly this is an imperfect standard but one that recognizes that there are variations in water quality that at least on a short-term basis exceed the objective of a 10 percent deviation in specific water quality parameters with no apparent effect on the listed species. Moreover, there are water quality parameters, such as pH and DO, for which a 10 percent deviation is inherently misleading. A 10 percent deviation in hydrogen ion concentration is unlikely to be consistently measurable while a 10 percent deviation in the logarithmic pH scale at near neutral conditions is in reality a change by a factor of 5 in hydrogen ion concentration. For oxygen, a 10 percent deviation is of little consequence until the oxygen reaches critically low levels that lead to organism stress or death. There is little clarity for most organisms as to how a 10 percent deviation in the water quality objective is to be applied and little information as to critical water quality levels that lead to adverse effects on the listed species.

A better approach to the water quality objective would be to relate observed variations in water quality to adverse effects on organisms and use that information to define the objective. For example, one could look to statistical techniques described by Harding et al. (2014) and Sutula et al. (2017) using such approaches as quantile regression or conditional probability analysis. Batiuk et al. (2009) provide an overview of setting DO criteria that also considers spatial challenges that may be critical, as well as duration and threshold conditions. In the absence of adverse effects, the observed variations in water quality would be a conservative indication of variations that can be safely experienced by the listed species. To maintain conservatism, a statistical measure, such as a variation in a specific water quality parameter within 95 percent of the distribution of historical observations of that parameter that do not lead to apparent adverse effects might be employed. **It is therefore recommended that the historical data in all available water quality parameters be analyzed, the distribution of observations that are not believed to lead to adverse effects be defined, and the biological objective for that water quality parameter be updated to reflect that analysis.**

## CONCLUSIONS AND RECOMMENDATIONS

**It is *likely* that the biological objectives will meet the biological goals for the fountain darter.** Fountain darters are clearly associated with SAV and there have been no recent downward trends in fountain darter densities by habitat type or systemwide changes in SAV coverage, despite the drought and flood years of 2013–2014 and 2015, respectively. The flow objectives are consistent with the habitat suitability modeling for fountain darters, and adaptive management was used successfully to adjust the long-term biological goals. The rating could be improved by repeating the habitat suitability modeling using more recent data; by further examining fountain darter median densities over time, by vegetative habitat type, and abundance indices both within reaches and systemwide; and by performing a power analysis on fountain darter data to guide the interpretation of false negatives.

**It is *likely* that the biological objectives will meet the biological goals for Texas wild rice.** This conclusion is based on empirical observations of gains in the coverage of Texas wild rice, even in the face of recent floods and droughts; on the compatibility of the flow objective with the habitat suitability model for Texas wild rice; and on the adaptive management changes that now include Texas wild rice as fountain darter habitat. As with the fountain darter, monitoring and successful restoration of Texas wild rice to date have led to conclusions offered with relatively high confidence. The rating could be improved by repeating the habitat suitability modeling using more recent data, by creating a defined water quality objective for Texas wild rice, and by adding a habitat objective to continue to remove nonnative SAV.

**It is *somewhat likely* that the biological objectives will meet the biological goals for the Comal Springs riffle beetle.** This conclusion is based on the limitations associated with (1) the lack of quantitative monitoring of CSRB populations, (2) determining whether riparian restoration can actually eliminate or significantly reduce siltation at spring openings, and (3) the lack of habitat suitability modeling for the CSRB in the monitored reaches. To improve the rating, the following actions should be undertaken. First, it is important to continue to standardize and move toward quantitative sampling of the CSRB in order to better understand what the true beetle populations are in the monitored reaches. Second, it is highly recommended that a plan be developed to quantitatively monitor CSRB habitat sedimentation associated with continuing riparian restoration efforts. The lack of data that link riparian erosion to spring orifice sedimentation represents a significant omission important to achieving the biological goals. Finally, if the habitat suitability modeling were repeated in the LTBG reaches, it would increase confidence in the ability of the flow objectives to meet the biological goals.

**It is *somewhat likely* that the biological objectives will meet the biological goals for the San Marcos salamander.** A robust monitoring program that could provide evidence of upward trends in abundance is lacking for this species. Much of the current scientific information on the species is based on observations and experiments with captive individuals. There is no water quality objective for the salamander or information on the effects of aquatic gardening. The rating could be improved by creating a water quality objective for San Marcos salamanders, better regulating recreational access to the 50-meter reach of the San Marcos River just below Spring Lake Dam, quantifying the outcomes of aquatic gardening and maintenance of silt-free gravel at the salamander study reaches, and augmenting the current sampling protocol with a new method to estimate proportion of area occupied and detection probability of San Marcos salamanders. Controlling access just below Spring Lake Dam and quantifying the maintenance of silt-free gravel should be made high priorities because they could be implemented soon and will help ensure that the stated salamander goals are met.

There are many documented occurrences of water quality parameters deviating more than 10 percent from their historical average with no noticeable impacts on the listed species. This calls into question the water quality objectives for the fountain darter and the CSRB. **Historical data on all available water quality parameters should be analyzed and the distribution of observations that are not believed to lead to adverse effects should be defined, so that the water quality objective for each parameter can be updated.**

## REFERENCES

Ahmadi-Nedushan, B., A. St-Hilaire, M. Bérubé, É. Robichaud, N. Thiémonge, and B. Bobée. 2006. A review of statistical methods for the evaluation of aquatic habitat suitability for instream flow assessment. River Research and Applications 22(5):503-523.

Batiuk, R. A., D. L. Breitburg, R. J. Diaz, T. M. Cronin, D. H. Secor, and G. Thursby. 2009. Derivation of habitat-specific dissolved oxygen criteria for Chesapeake Bay and its tidal tributaries. Journal of Experimental Marine Biology and Ecology 381:S204-S215.

BIO-WEST, Inc. 2007. Variable Flow Study: Seven Years of Monitoring and Applied Research. Prepared for Edwards Aquifer Authority, August.

BIO-WEST, Inc. 2014. Fountain Darter Movement under Low-Flow Conditions in the Comal Springs/River Ecosystem. Final Report. San Antonio, TX: Edwards Aquifer Authority.

BIO-WEST, Inc. 2017. Comal Springs Riffle Beetle *(Heterelmis comalensis):* Life History and Captive Propagation Techniques. Final Report prepared for the Edwards Aquifer Authority, December 27. http://www.eahcp.org/files/admin-records/NEPA-and-HCP/BIO-WEST_CSRB.life.hist_FINAL_20180126.pdf.

BIO-WEST, Inc. 2018. Habitat Conservation Plan Biological Monitoring Program San Marcos Springs/River Ecosystem.

BIO-WEST, Inc. and Watershed Systems Group, Inc. 2016. Submerged Aquatic Vegetation Analysis and Recommendations. Edwards Aquifer Habitat Conservation Plan. Contract No. 15-7-HCP. June.

Blanton and Associates. 2018. Edwards Aquifer Habitat Conservation Plan. 2017 Annual Report. Prepared for the U.S. Fish & Wildlife Service. March 26. http://www.eahcp.org/files/admin-records/NEPA-and-HCP/EAHCPAnnualReport2017v3_20180313_Redlined_from_Blanton.pdf.

Christin, P., and C. P. Osbourne. 2014. The evolutionary ecology of $C_4$ plants. The New Phytologist 204(4):765-781.

EAHCP (Edwards Aquifer Habitat Conservation Plan). 2016. Report of the 2016 Expanded Water Quality Monitoring Work Group. San Antonio, TX: EAHCP. June 23.

EARIP (Edwards Aquifer Recovery Implementation Program). 2012. Edwards Aquifer Recovery Implementation Program Habitat Conservation Plan. http://www.eahcp.org/files/uploads/Final%20HCP%20November%202012.pdf.

Ehleringer, J. R., T. E. Cerling, and B. R. Helliker. 1997. $C_4$ photosynthesis, atmospheric $CO_2$, and climate. Oecologia 112(3):285-299.

Fairweather, P. G. 1991. Statistical power and design requirements for environmental monitoring. Marine and Freshwater Research 42(5):555-567.

Furl, C. 2017. Conservation Measures, Biological Objectives, Biological Goals. Presentation to the National Academies Committee to Review the Edwards Aquifer Habitat Conservation Plan, October 2.

FWS (U.S. Fish and Wildlife Service). 1996. San Marcos and Comal Springs and Associated Aquatic Ecosystems (Revised) Recovery Plan. Albuquerque, NM: FWS.

Gore, J. A. 1989. Models for predicting benthic macroinvertebrate habitat suitability under regulated flows. Pp. 253-265 in Alternatives in Regulated River Management, J. A. Gore and G. E. Petts (eds.). Boca Raton, FL: CRC Press.

Grant, W., T. Swannack, R. Wang, T. Hardy, G. Ward, R. Doyle, T. Bonner, and BIO-WEST, Inc. 2017. Fountain Darter Modeling System for the Comal and San Marcos Rivers. Prepared for Edwards Aquifer Authority. May 19. http://www.eahcp.org/files/uploads/FDMS_FINAL_Report_20170612.pdf.

Green, R. H. 1989. Power analysis and practical strategies for environmental monitoring. Environmental Research 50(1):195-205.

Grossman, G. D., G. P. Jones, and W. J. Seaman, Jr. 1997. Do artificial reefs increase regional fish production? A review of existing data. Fisheries 22(4):17-23.

Harding, L. W., R. A. Batiuk, T. R. Fisher, C. L. Gallegos, T. C. Malone, W. D. Miller, M. R. Mulholland, H. W. Paerl, E. S. Perry, and P. Tango. 2014. Scientific bases for numerical chlorophyll criteria in Chesapeake Bay. Estuaries and Coasts 37(1):134-148.

Hardy, T. B. 2009. Technical Assessments in Support of the Edwards Aquifer Science Committee "J Charge" Flow Regime Evaluation for the Comal and San Marcos River Systems. River Systems Institute, Texas State University. https://smcorridornews.com/wp-content/uploads/2016/09/2009_Hardy_-FlowRegimeEvaluation.pdf.

Hardy, T. B., K. Kollaus, and K. Tower. 2010. Evaluation of the Proposed Edwards Aquifer Recovery Implementation Program Drought of Record Minimum Flow Regimes in the Comal and San Marcos River Systems. River Systems Institute, Texas State University. http://www.eahcp.org/files/admin-records/EARIP-HCP-docs/Hardy,%20Kollaus,%20Tower%202010.pdf.

Hatch, M. D., and C. R. Slack. 1966. Photosynthesis by sugarcane leaves. A new carboxylation reaction and the pathway of sugar formation. Biochemistry Journal 101:103-111.

Lamb, B. L., C. Sabaton, and Y. Souchon. 2004. Use of the instream flow incremental methodology: Introduction to the special issue. Hydroécologie Appliquée 14:1-7.

Mathur, D., W. H. Bason, E. J. Purdy Jr., and C. A. Silver. 1985. A critique of the in stream flow incremental methodology. Canadian Journal of Fisheries and Aquatic Sciences 42(4):825-831.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2017. Review of the Edwards Aquifer Habitat Conservation Plan: Report 2. Washington, DC: The National Academies Press.

Nelson, J. 1993. Population Size, Distribution, and Life History of *Eurycea nana* in the San Marcos River. M.S. Thesis, Texas State University.

Nowlin, W. H., P. Nair, and B. Schwartz. 2016. Final Report. Evaluation of the long-term elevated temperature and low dissolved oxygen tolerances of larvae and adult Comal Springs riffle beetle. EAHCP Project No. 146-15-HCP. http://www.eahcp.org/files/uploads/Nowlin_et_al._2017_EAA_2016_Applied_Research_-_CSRB_Long_Term_Temp_and_D....pdf.

NRC (National Research Council). 2015. Review of the Edwards Aquifer Habitat Conservation Plan: Report 1. Washington, DC: The National Academies Press.

Osenberg, C. W., C. M. St. Mary, J. A. Wilson, and W. J. Lindberg. 2002. A quantitative framework to evaluate the attraction–production controversy. ICES Journal of Marine Science 59(Suppl):S214-S221.

Railsback, S. 2016. Why it is time to put PHABSIM out to pasture. Fisheries 41:720-725.

Sage, R. F. 2004. The evolution of C4 photosynthesis. New Phytologist 161:341–370.

Smith, E. P., D. R. Orvis, and J. Cairns. 1993. Impact Assessment Before-After-Control-Impact (BACI) Model: Comments and Concerns. Canadian Journal of Fisheries and Aquatic Sciences 50:627-637.

Spence, D. H. N., and S. C. Maberly. 1985. Occurrence and ecological importance of $HCO_3$: Use among aquatic higher plants. Pp. 125–143 in Inorganic Carbon Uptake by Aquatic Photosynthetic Organisms: Proceedings of an International Workshop on Bicarbonate Use in Photosynthesis, August 18-22, 1984, Commemorating the Seventy-fifty Anniversary of the University of California, Davis, 1909-1984, W. J. Lucas and J. A. Berry (eds.). Rockville, MD: American Society of Plant Physiologists.

Sutula, M., R. Kudela, J. D. Hagy III, L. W. Harding, Jr., D. Senn, J. E. Cloern, S. Bricker, G. M. Berg, and M. Beck. 2017. Novel analyses of long-term data provide a scientific basis for chlorophyll-a thresholds in San Francisco Bay. Estuarine, Coastal and Shelf Science 197:107-118.

Tharme, R. E. 2003. A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. River Research and Applications 19:397-442.

Tupa, D. D., and W. L. Davis. 1976. Population dynamics of the San Marcos salamander, *Eurycea nana* Bishop. Texas Journal of Science 27:179-195.

Wang, P., G. Hu, and J. Cao. 2017. Stable isotopic composition of submerged plants living in karst water and its eco-environmental importance. Aquatic Botany 140:78-83.

# 4

# Will the Minimization and Mitigation Measures Meet the Biological Objectives?

This chapter addresses the second part of the Committee's statement of task, that is, whether the minimization and mitigation (M&M) measures are meeting the biological objectives. Rather than consider the dozens of M&M measures individually, this chapter is organized by *category* of M&M measure, with five major categories being identified: (1) flow protection measures, (2) measures to protect water quality, (3) planting of submerged aquatic vegetation (SAV) including Texas wild rice and removal of nonnative vegetation, (4) recreation management, and (5) riparian restoration. For each category, the section describes the relevant M&M measures and the extent of their implementation, it shows monitoring data when available, and it summarizes what is known about the effectiveness of the M&M measures. Each section concludes with a determination that the suite of measures in that category is (1) highly effective, (2) effective, (3) somewhat effective, (4) ineffective, or (5) effectiveness cannot be determined with available information. These ratings are parallel to those given in Chapter 3 in terms of the information necessary to achieve a certain rating and the role of uncertainty. Because the Committee did not separate out the contributions of individual M&M measures, it was not possible to determine whether all of the individual measures were required to meet that rating. Each section also suggests what might be done in the near future to increase the rating for that category.

TABLE 4-1 Flow Protection Measures in the Habitat Conservation Plan

| M&M Measure (HCP Section) | Spring System | Purpose |
|---|---|---|
| Voluntary Irrigation Suspension Program Option (5.1.2) | Comal and San Marcos | Reduces water withdrawals for irrigation based on irrigation well levels |
| Regional Water Conservation Program (5.1.3) | Comal and San Marcos | Reduces water withdrawals for municipal use based on conservation efforts such as leak detection and repair |
| Aquifer Storage and Recovery (5.5.1) | Comal and San Marcos | Water banking for later use |
| Critical Period Management Stage V (5.1.4) | Comal and San Marcos | 44% water withdrawal reduction for municipal, industrial, and irrigation use based on spring flow and index well water levels |

## FLOW PROTECTION MEASURES

The four flow protection measures of the Habitat Conservation Plan (HCP) are (1) Critical Period Management Stage V, (2) the San Antonio Water Supply Aquifer Storage and Recovery, (3) the Voluntary Irrigation Suspension Program Option (VISPO), and (4) the Regional Water Conservation Program (RWCP). These four flow protection measures (Table 4-1) are the most expensive elements of the entire HCP and comprised 71 percent of the HCP 2017 expenses, totaling $12.2 million through 2017 (Blanton and Associates, 2018). The measures have been designed to maintain the required minimum flows needed by the listed species in the Comal and San Marcos Spring systems during the Drought of Record and are applied in a Bottom-Up approach as needed to maintain those flows (Figure 4-1). Given the central importance of these two facts, a determination of whether these flow protection measures are effective is crucial to evaluating the overall success of the HCP.

An important tool for evaluating the flow protection measures is provided by the system responses to 2013–2014 drought conditions, since it is the only period when all five Critical Period Management stages[1] and

[1] The Critical Period Management stages I through IV predate the HCP, with precursor versions having originated from EAA rulemaking beginning in 1997 and amendments occurring thereafter, with eventual codification of the current version in the passage of Senate Bill 3 in 2007. The bill directed the EAA to adopt and enforce withdrawal reductions of up to 40 percent in the San Antonio Pool and 35 percent in the Uvalde Pool based on spring flow and


FIGURE 4-1 Bottom-Up approach for implementing the four spring flow protection measures. NOTE: Municipal Conservation Measures in the figure are the same as the Regional Water Conservation Program referred to in the text. SAWS ARS is the San Antonio water system aquifer storage and recovery program. SOURCE: HDR, Inc. (2011).

VISPO have been implemented to date. Both 2015 and 2016 were relatively wet years, and although 2017 saw a return to a drier cycle, only Stage I Critical Period Management was triggered (a 20 percent withdrawal reduction in the San Antonio Pool). The Aquifer Storage and Recovery system is not yet fully implemented but seeks to protect 50,000 ac-ft of Edwards permits from being withdrawn during certain drought conditions. The Regional Water Conservation Program is not expected to be fully implemented until 2020. Thus, these latter two programs have not yet been tested.

In the absence of observations during times of extreme drought, the basis for demonstrating the impacts of the flow protection measures on the flow in both systems is the MODFLOW model of the Edwards Aquifer. Since the original 2004 MODFLOW model was created to serve as the basis for the Bottom-Up program that frames the spring flow protection measures (HDR, Inc., 2011), significant steps have been taken to improve the modeling effort, not only to allow for a more accurate analysis of the four measures but also to provide a more effective management tool.

Adaptive management concepts have underpinned implementation and maintenance of the flow protection measures through monitoring progress and evaluating lessons learned. The Edwards Aquifer Authority (EAA) has

index well levels. Critical Period Management Stage V was developed under the HCP; hence it is referred to in Table 4-1 and Figure 4-1. Details on all five CPM plan stages are presented in a later section of this chapter.

also taken steps to look beyond these flow protection measures by exploring other aspects of water quantity optimization, including continued assessment of aquifer hydraulics, collaboration with the U.S. Department of Agriculture Natural Resources Conservation Service conservation activities within the EAA, recharge protection, and long-term aquifer storage strategies (Hamilton and Boenig, 2017).

In this section, updates on the four flow protection measures are provided, followed by a discussion of MODFLOW model refinements and reduction of uncertainty since Report 2 (NASEM, 2017). The section ends with a determination of whether the flow protection measures can achieve the flow component of the biological objectives in the HCP (see Chapter 3 for details on the flow objectives for the Comal and San Marcos systems).

### Voluntary Irrigation Suspension Program Option

VISPO involves voluntary enrollment by irrigation permit holders for a five- or ten-year period, requiring enrolled permit holders to suspend pumping for one year in the event of triggering condition in index well J-17. Specifically, if on October 1 of the prior year the water-level elevation in J-17 drops to equal or below 635 ft mean sea level, this trigger occurs. Participants receive an annual payment ("Standby Fee") of $50/ac-ft of the pledged withdrawal rights under the VISPO Forbearance Agreement. In years when a suspension of water use is mandated by the trigger, participants receive an additional Forbearance Payment, which equals $150/ac-ft per annum of the pledged withdrawal rights that the permittee will be unable to withdraw. The Standby Fee and Forbearance Payment are increased each year by 1.50 percent, compounded annually, starting with the year after the agreement became effective.

There are two types of withdrawal rights encompassed by the program: (1) Base Irrigation Groundwater that is restricted to irrigation use, and (2) Unrestricted Irrigation Groundwater that is not restricted by location or purpose. VISPO enrollees to date have preferred the Base over the Unrestricted program by a factor of more than 3:1.

The VISPO enrollment goal of 40,000 ac-ft was met in 2014 and is now 40,921 ac-ft. Many individuals enrolled in the late summer and early fall of 2014 as it became clear that restrictions would likely be triggered in 2015. The J-17 indicator well was below 635 ft on October 1, 2014, and the VISPO program was triggered throughout 2015. Because of abundant precipitation in 2015 and 2016, VISPO was not triggered in 2016 or 2017. As a result, the permit holders could use the enrolled water.

Payouts for VISPO through 2017 totaled $2.21 million (Blanton and Associates, 2018). Renewal of the VISPO agreements will be important since 42 agreements totaling 9,489 ac-ft will expire at the end of 2018.

### Regional Water Conservation Program

The RWCP allows municipal, industrial, and exempt private well owners to offset their pumping through a series of conservation measures, including leak detection, use of high-efficiency plumbing, commercial or industrial retrofit rebates, and water reclamation. Under the HCP, the goal of this program is 20,000 ac-ft, where half of the conserved groundwater will be available for pumping and the other half is placed in a Groundwater Trust, thereby reducing stress on the aquifer and springs (Blanton and Associates, 2017). As an example, near the end of 2016, the City of Uvalde distributed more than 525 high-efficiency, low-flow toilets and more than 500 plumbing kits to city residents. The San Antonio Water System (SAWS) is implementing a five-year leak detection and repair program that alone may nearly satisfy the goals of the RWCP due to estimated savings totaling 19,612 ac-ft, half of which will be held in the Groundwater Trust and is not to be pumped through 2028 (Blanton and Associates, 2018).

### Aquifer Storage and Recovery

SAWS Aquifer Storage and Recovery (ASR) facility is the most expensive of the four flow protection measures. Withdrawn groundwater from the Edwards Aquifer is pumped via pipeline and stored underground in the Carrizo Aquifer at the SAWS ASR facility in south Bexar County. In the event of severe aquifer conditions in the Edwards and spring flow conditions at Comal Springs, ASR water could be recovered at SAWS discretion and redistributed to San Antonio when demand is high in order to offset any prescribed forbearance of permitted Edwards withdrawals required of SAWS under this program (EARIP, 2012; EAA and SAWS, 2013).

The overall goal of the ASR program is for the EAA to acquire 50,000 ac-ft through lease and forbearance agreements, for a total of up to 176,000 ac-ft potentially required to be forborne between the EAA (50K) and SAWS (126K) during the prescribed drought conditions that trigger forbearance. A total of 126,000 ac-ft could be redistributed by SAWS to its customers during such drought conditions. Through 2017, 32,583 ac-ft was leased by permit holders for SAWS ASR storage toward the spring flow protection goal, bringing the total storage to 82,708 ac-ft (Blanton and Associates, 2018).

Two mutually beneficial programs, the ASR Leasing Program and the ASR Pooling Program, offer opportunities to permit holders while achieving conservation benefits and storage in the event of Drought-of-Record conditions. The ASR Leasing Program offered 1-, 5-, 7-, 10-, and 15-year terms for specified volumes of unrestricted groundwater. With a 5-year lease, for example, the program annually pays $140/ac-ft. This leasing program is ideal for permit holders who know they will not need specific volumes of water over the agreed-upon lease period. In 2018, the EAA discontinued accepting or renewing ASR leases because the SAWS ASR will soon be recharged with sufficient groundwater to meet the EAA's and SAWS' storage obligations under this program. For this reason, the EAA has shifted its focus to obtain forbearance agreements (rather than leases or lease options) to fill out the remainder of the 50,000 ac-ft.

The ASR Pooling Program is more flexible, while incentivizing conservation through fiscal compensation. This program allows the permit holder to pool unpumped groundwater withdrawal rights at year's end. The cumulative pool created by program participants may be used to offset regional contributions to the ASR in support of the HCP. Program participants are paid $50/ac-ft for the portion used for pooling purposes.

A change to the ASR program occurred in early 2018, after consideration of lease marketability and simulation results using the updated version of the MODFLOW groundwater flow model. The lease options were simplified and reduced from three to two leasing tiers, which are now coordinated with new, long-term forbearance agreements. All agreements are now sliding acre-foot scales, and the forbearance agreements are exercised in the year after the 10-year moving annual average of the Edwards recharge falls to 500,000 ac-ft/yr or below. This recharge value is a decrease of 72,000 ac-ft/yr from the original HCP (EARIP, 2012). Scenarios are also being explored involving the use of water elevations in index well J-17 as a trigger rather than 10-year rolling average recharge estimates. Given the uncertainty in recharge rates, this seems to be a prudent approach.

In NASEM (2017), potential water quality concerns were raised regarding the SAWS ASR. Although the EAA considers this to be a SAWS issue, given the importance of the ASR facility to the HCP, the Committee reiterates a few important issues. While available data suggest that water quality concerns related to metals mobilization are not currently present, conditions or activities could occur that may lead to mobilization of metals as an ASR facility expands its storage volume, which is planned for the SAWS H2Oaks ASR facility (formerly Twin Oaks ASR). Operational activities may yield changes in aquifer oxidation-reduction conditions such that constituents can be mobilized where none occurred or were detected before. One example is exposure of native (unaffected) aquifer rocks/sediments to stored water as the storage zone expands. Moreover, detection of mobilized metals can be missed because the release of arsenic, molybdenum, and related constituents can be a function of sample frequency and timing relative to operational cycle stages for each well (i.e., recharge, storage, or recovery) and location of sampling wells relative to the expanding mixing zone (Arthur et al., 2005, 2007).

### Critical Period Management Stage V

The five-stage Critical Period Management Program is in place to ensure that aquifer levels and spring flows are sustained above specific thresholds during Drought-of-Record conditions. These conditions are specific to the two main pools in the aquifer, the San Antonio and Uvalde pools. In the San Antonio pool, critical parameters are water levels in index well J-17 and flow rates at San Marcos Springs and Comal Springs (Figure 4-2). Water levels in index well J-27 are taken to represent Uvalde Pool conditions. Withdrawal reductions from the Edwards Aquifer are implemented through layered management scenarios involving groundwater conservation measures and use of alternative water supplies (EARIP, 2012). The hydrologic conditions that trigger each management layer can be evaluated using MODFLOW simulations that would theoretically sustain spring flows across Drought-of-Record conditions.

Critical Period Management Stage V is the most restrictive in terms of withdrawals, requiring maximum withdrawal reductions up to 44 percent. For perspective, "it is anticipated that during Stage V, all outdoor use of groundwater withdrawn from the aquifer will be prohibited, except for limited circumstances, such as foundation watering, watering from a handheld hose, and emergency uses such as firefighting" (EARIP, 2012). At the other end of the spectrum, Stage I triggers no reduction in withdrawals from the Uvalde Pool and a 20 percent reduction in withdrawals from the San Antonio Pool. The specifics of triggering conditions are based on statistics and duration of the conditions, as are mechanisms for downgrading critical period stages. For example, in the San Antonio pool, "in order to enter into Critical Period Stage V, the applicable spring flow trigger is either less than 45 cfs based on a ten-day rolling average, or less than 40 cfs, based on a three-day rolling average. Expiration of Critical Period Stage V is based on a ten-day rolling average of 45 cfs or greater" (Blanton and Associates, 2017).

As noted previously, Stage V was triggered for the Uvalde Pool from March 2013 through 2014 and into early 2015. In the San Antonio Pool, Stage II, III, or IV restrictions were in place from 2013 to 2015, including 142 days in Stage IV during 2014 (Blanton and Associates, 2015). In 2016, no stage of the Critical Period Management Program was triggered owing to increased aquifer levels and spring flows during the period (Blanton and Associates, 2017). Decreased aquifer levels and spring flows during 2017 resulted in two separate triggers of Stage I in the San Antonio Pool for a total of 61 days, resulting in a reduction of 3.4 percent to all permits (Blanton and Associates, 2018). Stage II was triggered in June 2018 in the San Antonio Pool.

**Table 3.1-3.** Critical Period Management Program Triggers, Stages, and Reductions for the San Antonio Pool of the Edwards Aquifer

| Wells/Springs | Critical Period Stage I* | Critical Period Stage II* | Critical Period Stage III* | Critical Period Stage IV* | Critical Period Stage V** |
|---|---|---|---|---|---|
| Index Well J-17 Level (msl) | <660 | <650 | <640 | <630 | <625 |
| San Marcos Springs Flow rate (cfs) | <96 | <80 | N/A | N/A | N/A |
| Comal Springs Flow rate (cfs) | <225 | <200 | <150 | <100 | <45** or <40** |
| Withdrawal Reduction | 20% | 30% | 35% | 40% | 44% |

* A change to a critical period stage with higher withdrawal reduction percentages, including initially into Stage I for the San Antonio Pool and Stage II for the Uvalde Pool, is triggered if the 10-day average of daily springflows at the Comal Springs or the San Marcos Springs or the 10-day average of daily Aquifer levels at the J-17 or J-27 Index Wells, as applicable, drop below the lowest number of any of the trigger levels for that stage. A change from any critical period stage to a critical period stage with a lower withdrawal reduction percentage, including exiting from Stage I for the San Antonio Pool and Stage II for the Uvalde Pool, is triggered only when the 10-day average of daily springflows at the Comal Springs and the San Marcos Springs and the 10-day average of daily Aquifer levels at the J-17 or J-27 Index Wells, as applicable, are all above the same stage trigger level.

** In order to enter into Critical Period Stage V, the applicable springflow trigger is either less than 45 cfs based on a ten-day rolling average or less than 40 cfs based on a three-day rolling average. Expiration of Critical Period Stage V is based on a ten-day rolling average of 45 cfs or greater.

**Table 3.1-4.** Critical Period Management Program Triggers, Stages, and Reductions for the Uvalde Pool of the Edwards Aquifer

| Wells/Springs | Critical Period Stage I* | Critical Period Stage II* | Critical Period Stage III* | Critical Period Stage IV* | Critical Period Stage V** |
|---|---|---|---|---|---|
| Index Well J-27 Level (msl) | N/A | <850 | <845 | <842 | <840 |
| San Marcos Springs Flow rate (cfs) | N/A | N/A | N/A | N/A | N/A |
| Comal Springs Flow rate (cfs) | N/A | N/A | N/A | N/A | N/A |
| Withdrawal Reductions | N/A | 5% | 20% | 35% | 44% |

* A change to a critical period stage with higher withdrawal reduction percentages, including initially into Stage I for the San Antonio Pool and Stage II for the Uvalde Pool, is triggered if the 10-day average of daily springflows at the Comal Springs or the San Marcos Springs or the 10-day average of daily Aquifer levels at the J-17 or J-27 Index Wells, as applicable, drop below the lowest number of any of the trigger levels for that stage. A change from any critical period stage to a critical period stage with a lower withdrawal reduction percentage, including exiting from Stage I for the San Antonio Pool and Stage II for the Uvalde Pool, is triggered only when the 10-day average of daily springflows at the Comal Springs and the San Marcos Springs and the 10-day average of daily Aquifer levels at the J-17 or J-27 Index Wells, as applicable, are all above the same stage trigger level.

** In order to enter into Critical Period Stage V, the applicable springflow trigger is either less than 45 cfs based on a ten-day rolling average or less than 40 cfs based on a three-day rolling average. Expiration of Critical Period Stage V is based on a ten-day rolling average of 45 cfs or greater.

FIGURE 4-2 Critical Management Program triggers for the San Antonio and Uvalde pools. SOURCE: Blanton and Associates (2018).

## Refinement of the MODFLOW Model

Hydrologic modeling serves two principal objectives in the HCP: (1) to simulate spring flows during a repeat of the Drought of Record to determine if implementation of the Bottom-Up package of the four flow protection measures will be effective and (2) to serve as a predictive tool for other water resource management and conservation scenarios. The Committee's first two reports made several observations that present model challenges and many recommendations pertaining to evaluating and reducing model uncertainty.

Some of the Committee's recommendations about the hydrologic modeling have been addressed by the EAA team. For example, improvements have been made in the hydrologic conceptual model. The EAA has conducted a sensitivity analysis of recharge estimates and boundary flow along the contributing zone (the latter being the focus of the Interformational Flow Program). Furthermore, PEST (Model-Independent Parameter Estimation software) runs of numerous models reflecting different recharge scenarios are complete, and the Bottom-Up package has been optimized using the updated and recalibrated MODFLOW model. The results of updated Bottom-Up analysis were presented by Jim Winterle in January 2018 and indicate that the minimum flow at Comal Springs for the August 1956 Drought of Record is 10 percent greater than the original MODFLOW Bottom-Up results (using all four flow protection measures; Figure 4-3). Similar results were observed for the updated San Marcos Springs Bottom-Up analysis.

In NASEM (2017), there was the suggestion to validate the model by testing it against periods of data that were not used in the calibration, specifically during the more recent drought of 2011 to 2014, as well as the wet year of 2015. As noted above, this period includes periods of Critical Period Management restrictions, including Stage V in the Uvalde Pool and the triggering of VISPO in 2014 for the 2015 year. This validation has been conducted, and the model shows general agreement with the well levels and the spring flow observations, but with periods of substantial deviation. For example, during the validation period, several peak water levels in J-17 occur more than 10 feet below observed values, with few paired data points tightly matching as well as during the pre-2011 period (Figure 4-4). The low flows are also underestimated by the model but match within 5 feet except for one point in 2013, which is approximately 15 ft below observed. There exists better agreement in the J-27 simulation for the validation period; however, a strong divergence begins after May 2015, with differences between simulated and observed water levels on the rising limb of the hydrograph exceeding 20 feet. Likewise, spring flow measurements at Comal Springs during the validation period match less well than the calibration

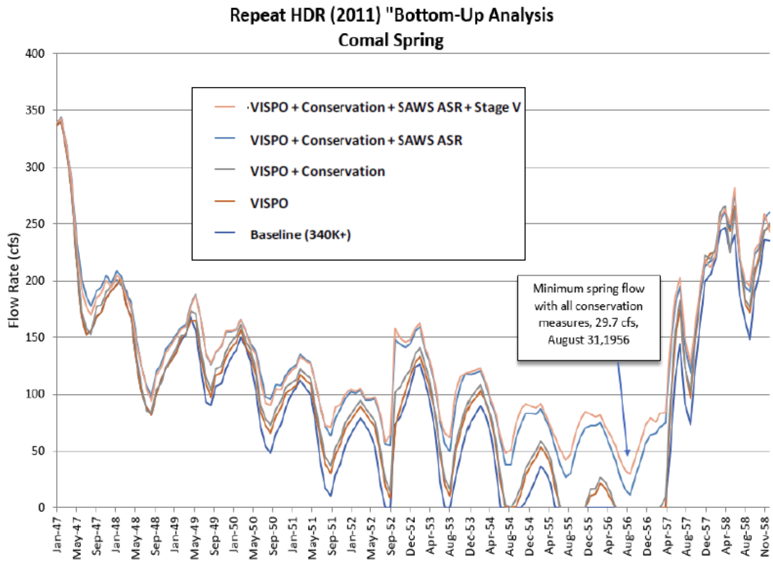



FIGURE 4-3 Updated Bottom-Up analysis for Comal Springs with HDR, Inc. (2011) assumptions. SOURCE: Modified from Winterle (2018).

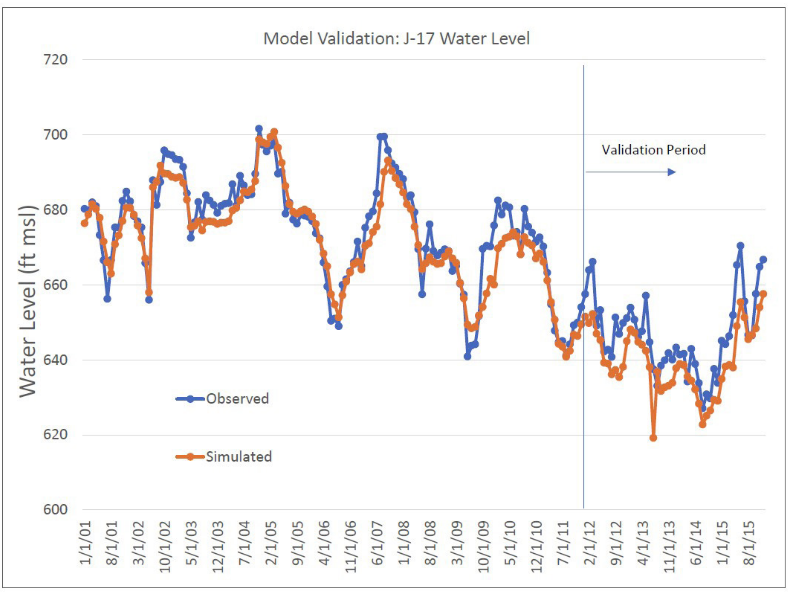



FIGURE 4-4 Validation of updated MODFLOW model for J-17 water levels. SOURCE: Winterle (2018).

period and are 50 cfs or more below observed rates at both peak and low flows (Figure 4-5). San Marcos simulated and observed flow rates exhibit less error in the low flows, with exception of simulated peaks greater than 50 cfs in the latter part of the validation period and a low-flow simulation approximately 25 cfs below observed. Uncertainty in model validation against observed water-level elevations and spring flows is expected given the scale, hydrologic dynamics, and hydrogeologic complexities within the model domain. In general, errors were greater at peak flows than low flows during the validation period, and the calibration period shows greater differences at peak flows, with generally better agreement at low flows.

The greatest model underpredictions tend to occur during periods of rapid recovery, with the simulations showing slower recovery in water-well levels. Underprediction of the indicator well levels and prediction of a slower recovery during wet periods means that the model is conservative—in the sense of protecting the listed species and the spring ecosystems—because it overpredicts the impacts of dry conditions on water levels in the wells. This is not necessarily true in all conditions, but it is reassuring that the model either matched or conservatively predicted indicator-well levels during a period characterized by drought conditions, when water restrictions were in place, and during a period of validation and not calibration.

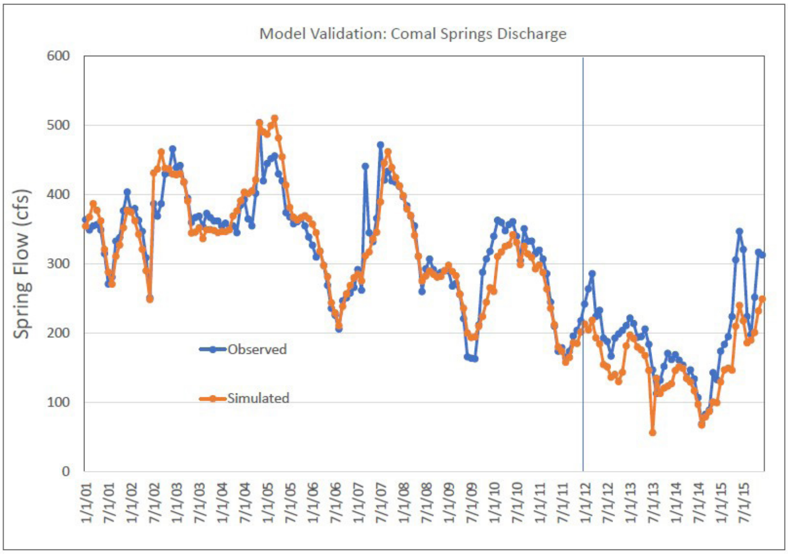



FIGURE 4-5 Validation of updated MODFLOW model for Comal Springs discharge. SOURCE: Winterle (2018).

NASEM (2017) also recommended addressing model versioning and peer review of each new version. Liu et al. (2017) provide an excellent example of implementation of this recommendation, including insightful external peer-review comments maintained verbatim in the report appendix. Completion of additional uncertainty analysis using PEST++ inverse parameter estimation software is anticipated during the next year, including evaluation of uncertainty in hydraulic parameters and recharge quantity distribution, as well as simultaneous inverse parameter estimation of the 2001–2015 period and the 1947–1958 Drought of Record (Winterle, 2018).

The continuing modeling efforts of the EAA, including validation and uncertainty analysis, are on the right track. Many advances have been accomplished to reduce model error to below the proposed criterion for spring flow calibration statistics (Table 4-2). Note that the model errors, as shown in Table 4-2, are large compared to the HCP minimum monthly flow requirements. For comparison, the HCP minimum flow for Comal Springs is 45 cfs (minimum monthly average) and for San Marcos Springs is 52 cfs (minimum monthly average). In particular, the updated model root mean square (RMS) error is more than half of the minimum average monthly flow rate for the springs. The RMS error tends to emphasize larger deviations which, as indicated above, may be dominated by higher flow periods during recovery from dry weather and not by the drought periods themselves. Maximum absolute error reflects the greatest observed error between the model simulation and observed values. These errors (Table 4-2) are more than double the minimum flows. It is noteworthy that the errors represent the entire model period, including the calibration and validation periods for the updated model. Given the need to estimate minimum flows, it may also be useful to focus on errors during periods of low flow, for example, the magnitude and direction of the RMS and maximum deviations at the minimum flow.

TABLE 4-2 Spring Target Calibration Summary

| Error Statistic | Proposed Criterion, cfs | Original 2004 Model, cfs | Updated Model, cfs |
|---|---|---|---|
| Comal Springs RMS error | ≤50 | 37.9 | 26.2 |
| Comal Springs maximum absolute error | ≤150 | 139 | 79.7 |
| San Marcos Springs RMS error | ≤35 | 62 | 28.0 |
| San Marcos Springs maximum absolute error | ≤150 | 134 | 114.3 |

SOURCE: Data from Winterle (2018).

### Will the Flow Protection Measures Meet the Flow Objectives?

Although model refinements continue to reduce uncertainty, it is difficult to assess the degree to which the model can achieve the original goal of validating the Bottom-Up package because the model error is proportionally high compared to the required minimum flows, and not all of the Bottom-Up package has been implemented and validated by model simulation runs. However, two droughts have been modeled using flow protection measures. The model of the Drought of Record showed flows above triggers when flow protection measures were applied (Figure 4-3). In addition, model validation during periods of Stage V restrictions in the Uvalde Pool and Stage IV restrictions in the San Antonio Pool as well as during periods of VISPO triggering in 2014 suggest that the model has been successful in conservatively estimating both indicator-well levels and minimum spring flows. Furthermore, the model predictions tended to be conservative at low flows during the validation period. Finally, throughout the 2014 drought during which Critical Period Management measures reached Stage IV in the San Antonio pool and Stage V in the Uvalde Pool, spring flows remained above threshold levels. Some uncertainty will remain regarding the effectiveness of the flow protection measures until each stage has been triggered (e.g., ASR for both springs and Stage V for the San Antonio pool). Taking all of this information into account, the Committee concludes that the flow protection measures will be **effective** in meeting the flow component of the biological objectives for all listed species.

Certain activities and outcomes could further improve confidence in the flow protection measures and lead to a higher rating. Model validation should continue into the future as new periods of drought arise, which can test the Bottom-Up package and other scenarios (see Chapter 5). In addition, an uncertainty analysis is presently under way, but the results will not be available until 2019. If the uncertainty analysis shows that a parameter such as intraformational flow or recharge is overestimated, then low-flow periods predicted by the model are not as conservative. In this case, the flow protection measures should be updated and perhaps new triggers should be considered in Phase 2 of the HCP. Moreover, there might be a more precipitous decline in spring flow than predicted by the model in the case of unevenly distributed recharge leading to asymmetrical drought. The flow protection measures need to be robust enough to address these alternative scenarios. The rating for flow protection measures could move toward highly effective if results of the uncertainty analysis show that errors are low or if model improvements continue to demonstrate that the model is biased low (i.e., conservatively underestimates well levels and spring flows).

## WATER QUALITY PROTECTION MEASURES

This section considers the M&M measures designed to protect water quality in the Comal and San Marcos river systems (Table 4-3). These include stormwater control measures, golf course management, and the management and removal of litter and floating vegetation. These measures are appropriately directed toward watershed activities and not direct action in the river systems, with the exception of removing litter and floating vegetation. An Applied Research project indicated that direct control of dissolved oxygen in Landa Lake was likely not effective, as was addressed in the Committee's previous report (NASEM, 2017). This discussion focuses primarily on watershed management through stormwater control plans. (Note that other activities in the river such as bank stabilization and recreation management are discussed in subsequent sections.)

The water quality protection measures are meant to achieve the biological objective of maintaining water quality within 10 percent of historical conditions. However, for the Comal Springs riffle beetle, this objective ap-

TABLE 4-3 Water Quality Protection Measures in the Habitat Conservation Plan

| M&M Measure (HCP Section) | Spring System | Target Contaminants | Purpose |
|---|---|---|---|
| Low-impact development/BMPs (5.7.3) | San Marcos | Sediment, flow | Prevent contamination from entering rivers via stormwater runoff |
| BMPs for stormwater control (5.7.6) | Comal | Sediment, flow | Prevent contamination from entering rivers via stormwater runoff |
| Management of floating vegetation mats and litter removal (5.3.3 and 5.4.3) | Comal<br>San Marcos | Low DO | Remove algae and vegetation from spring openings in Spring Lake; to avoid entanglement with TWR; litter removal |
| Decaying vegetation removal program (5.2.4) | Comal | Low DO | Prevent decaying vegetation from lowering DO in Landa Lake |
| Golf course management (5.2.11, 5.4.9) | Comal<br>San Marcos | Pesticides, nutrients | Prevent chemicals applied to the golf courses from entering rivers |

NOTE: BMP = best management practices; DO = dissolved oxygen; TWR = Texas wild rice.

plies to spring water quality, which is not a target of the M&M measures being evaluated here. Hence, this section pertains most directly to the water quality component of the biological objective for the fountain darter. Chapter 3 has already discussed the peculiarities of this objective, such as the fact that the criterion of 10 percent deviation is not clearly defined and makes little sense for some parameters, such as pH. The discussion below will instead focus on the effectiveness of measures to maintain or improve water quality and recognizes that appropriately measuring success is an important and ongoing challenge.

## Stormwater Control Measures

The City of San Marcos lies in one of the most rapidly developing counties in the country, with a reported 61 percent population increase from 2000 to 2010 (John Gleason LLC, 2017). The City of New Braunfels, through which the Comal Spring River flows, is considered fully developed, but increased development is expected in outlying areas, such as the Blieders Creek headwaters northwest of the city. With this population growth and development come impervious surfaces, such as roads, parking lots, and structures. Impervious surfaces reduce infiltration of stormwater, resulting in increased overland flow to streams, carrying with it any pollutants on roadways and other surfaces. One of the most important pollutants in stormwater is sediment, which can accumulate in portions of the Comal and San Marcos rivers and degrade habitat. NASEM (2017) indicated that removal of sediment from the river is likely to be ineffective without control of the source of these sediments. The rapid flow of stormwater to streams increases stream discharge, further disrupting habitats. This combination of stressors (increased flow and pollutant loading) from urban development is known as "urban stream syndrome" (Walsh et al., 2005). Entities in both the Comal and San Marcos watersheds have developed plans to try to reduce the impact of new and existing development.

A number of different terms are used to describe efforts to minimize the detrimental effects of stormwater. Low-impact development refers to plans that govern how construction projects operate to reduce impacts on both stormwater and resource use. Green infrastructure encompasses a wide variety of techniques for capturing stormwater and trying to mimic the natural water cycle, rather than just using stormwater piping systems. Stormwater control measures (SCMs), also referred to as best management practices (BMPs), are used to capture stormwater and enhance infiltration. By enhancing infiltration, SCMs can minimize pollutant loads (e.g., nutrients and sediments) entering the stream through stormwater runoff and reduce high flows, which can damage aquatic habitats. SCM is the term adopted in this report to be consistent with previous National Academies guidance (NRC, 2009).

Various techniques are used to reduce stormwater flows to streams, and thus reduce stream discharge (Davis, 2005; Geosyntec Consultants and Wright Water Engineers, Inc., 2009; NRC, 2009). SCMs typically involve capturing stormwater, storing it during storm events, and infiltrating it to provide a slower, filtered pathway to stream discharge points. SCMs that can cut peak storm flows, reduce volumes, and capture sediment and other contaminants are also important because they have the potential to decrease habitat disruption caused by erosion (Walsh et al., 2005; Hood et al., 2007). Water can be captured by using topography to direct flow to basins or by piping water from streets or roofs to underground chambers. When plants are used to maintain infiltration pathways and enhance evapotranspiration, it is referred to as a bioinfiltration basin. Implementation of basins typically requires a larger area, where underground chambers can be constructed in a large or small size to fit in between existing structures or along streets. Another type of SCM is bank stabilization, which can be used to reduce erosion in areas of high flow by use of rock walls, and other structures along a bank; this bank erosion contributes to sediment loads and habitat loss in streams. Bank stabilization projects are categorized as recreational M&M measures in the HCP and discussed in a subsequent section of this chapter.

Although SCMs have been used for decades to manage stormwater, it is difficult to assess their effectiveness because monitoring has been limited and is challenging (Strecker et al., 2001; NRC, 2009), although efforts to compile data on SCM effectiveness are under way (Leisenring et al., 2014). For example, SCMs are assumed to reduce pollutant loads, particularly from roadways, but unless the input loading is measured, the efficacy of the pollutant reduction is unknown; thus, typical load reductions may not apply for site-specific source terms. The tracking of pollutant loads is also difficult due to multiple sources and pathways (Fletcher et al., 2013; Filoso et al., 2015). The impact of SCMs on stream health is difficult to assess because of fragmented implementation and uncertainties in performance (Roy et al., 2008). By some estimates, measurable impact occurs only when the density of projects approaches the density of development, which is extraordinarily costly (Lui et al., 2015; Vogel et al., 2015; Bell et al., 2016). Efforts continue to develop appropriate assessment techniques for SCMs, including the development of treatment trains and principles for matching capacity to flow regimes (Loperfido et al., 2014; Walsh et al., 2016).

Failure of basins, often due to clogging, diversion of stormwater (lack of capture), or incorrect leveling of outfall structures, is not uncommon (e.g., Livingston, 2000; Emerson et al., 2005; Brown and Borst, 2014) particularly in the initial period after construction. Retrofitting basins to fix these issues is now a part of SCM treatments.

Initial planning for stormwater control in the HCP (EARIP, 2012, App. L) focused on reducing pollutant loads. The HCP made several recommendations, although specific targets were not spelled out. The plan recommended limiting impervious cover; reducing stormwater runoff into the Old Channel, Landa Lake, Spring Lake, and the recharge and contributing zones; and banning the use of coal tar sealants to reduce polycyclic aromatic hydrocarbons in runoff from roadways and parking lots. In the Comal Springs system, street-sweeping programs have been implemented to reduce loading from street runoff. The HCP also directed development of a water quality monitoring program. However, the monitoring program was not tied to evaluating stormwater control measures or directing management of stormwater control; rather, the water quality monitoring plan more broadly evaluated stream health along target reaches.

While the initial plans included incentive programs to encourage private development of SCMs, the more recent plans (described below) emphasize development of SCMs on public property (or Texas State University property). This shift in focus recognizes the need for access to larger areas for stormwater control, the costs associated with construction, and the need for maintenance after construction, which are all more readily available through public entities (or large landowners). The stormwater management plans abide by the Texas Commission on Environmental Quality volume requirement to store the first ½ inch of rain for 24 hours. The plans now include recently enacted ordinances requiring stormwater management plans for sites that involve 5,000 $ft^2$ of development, including guidelines for construction practices. Both the Comal and San Marcos communities also include public outreach and education in their plans, pollution prevention in vulnerable areas such as parking lots and critical habitats, and maintenance activities for the SCMs.

The City of New Braunfels Water Quality Protection Plan (WQPP; Alan Plummer Associates, 2017) and the WQPP for San Marcos and Texas State University (John Gleason LLC, 2017) proposed several measures to reduce impacts of stormwater on the aquatic habitats of the Comal and San Marcos Springs river systems. The SCMs proposed in the WQPPs for both cities, and the attempts to prioritize projects, are typical of stormwater remediation methods for urban systems. Given that most urban streams cannot be returned to pristine conditions, the goals of stormwater management in these two systems are stabilizing the stream system, reducing flows and pollutant loads, and improving development practices.

TABLE 4-4 Cost Comparisons for Sediment Removal and Stormwater Control Projects in Sessom Creek

| Metric | Project 1. Existing Sediment Removal Project | Project 2. Stream Restoration of Reach 2 (including RPS 9 and 10) | Project 3A. Stream Restoration of Windmill Tributary | Project 3B. Stormwater BMP for Windmill Tributary w/ limited restoration |
|---|---|---|---|---|
| Pounds of TSS Removed per year | 159,780 | 190,383 | 800 | 46,336 |
| Total Capital Cost (1) | $744,292 | $1,250,000 | $141,250 | $197,015 |
| Annualized Cost ($/yr) | $186,073 | $74,183 | $9,270 | $16,534 |
| Cost per pound TSS removed (2) | $1.16 | $0.39 | $11.59 | $0.36 |

(1) Total Capital Costs for Projects 2 and 3 includes preliminary engineering, design, and construction phases
(2) Calculated as Whole Life Cycle Cost divided by Pounds of TSS Removed per year

NOTE: TSS = total suspended solids, BMP = best management practices.
SOURCE: John Gleason LLC (2017).

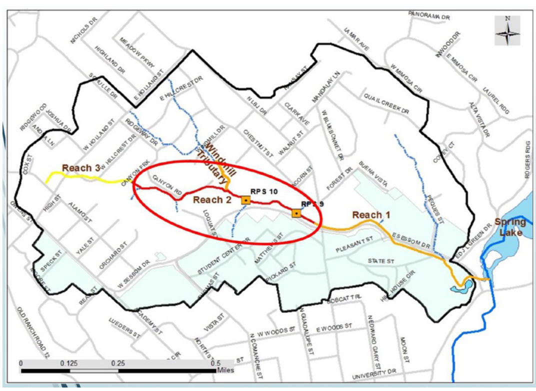
### *San Marcos System*

The SCM plans in the San Marcos system are focused on Sessom Creek. This tributary is a major contributor of sediment to the San Marcos River because of the large impervious surface area in the subwatershed, high flows, and erodible soils (John Gleason LLC, 2017). Attempts to mitigate the sediment input to the main channel by removing sediment have not been cost-effective due to recurring inputs (NASEM, 2017). The types of SCMs proposed have been evaluated in terms of cost, funding potential, sediment removal potential, and land opportunities (John Gleason LLC, 2017). Typical projects proposed are bank stabilization, stream reconnection, wet ponds, wetland retrofitting, and detention basins. Using multiple SCMs in a focused area is a good strategy for increasing the impact of stormwater control, and Sessom Creek represents a reasonable target. Approximately 50 projects have been proposed, but initially three projects in the middle reach have received permitting (Table 4-4, Figure 4-6a) and are paid for in part by HCP funding that was redirected from sediment removal operations. It is not clear how many SCMs will ultimately be installed or the pace of projects per annum. In addition, monitoring where Sessom Creek enters the main stem (Figure 4-6b) will be initiated, including stream gauging for the first time, water quality monitoring, and stormwater sampling. The water quality monitoring includes turbidity sensors.

SCMs were also proposed close to East Hopkins Street, with sediment removal ponds scheduled to be constructed early in 2018, and rain gardens and a bioinfiltration basin were recently completed near C. M. Allen Park-way. The initial SCMs were close to the street and stream, but modifications of the initial plans were approved. Sediment storage ponds are now located on public property, but farther from the stream than the initial proposed locations in the HCP. A comparison of the capture areas for the new locations relative to the initial design was not provided.

A number of additional SCMs are mentioned in the San Marcos WQPP, including rain gardens, wet ponds, bioinfiltration basins, constructed wetlands, stormwater reuse, natural area conservation (purchasing land for protection from development), and turf management (Figure 4-7). Design proposals have been evaluated for their capture areas, nutrient reduction, and sediment reduction potentials. However, there was no timetable proposed for these additional measures, and the implementation is dependent on available funding. Any prioritization of sites and monitoring has yet to occur.

**A**




**B**


FIGURE 4-6 (A) Sessom Creek stormwater control projects in the middle reach and (B) monitoring for Sessom Creek input to the main stem of the San Marcos River. SOURCE: Pence (2018).

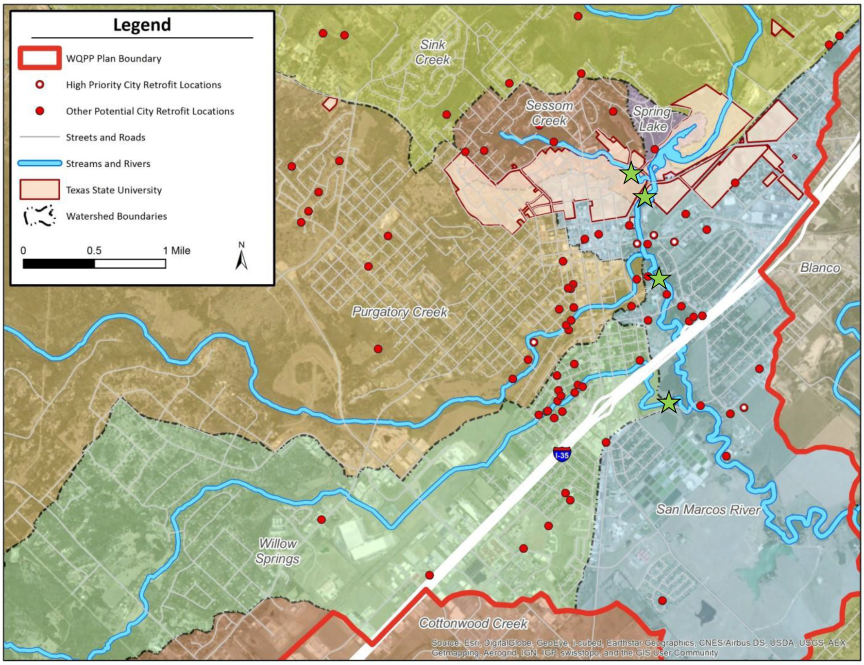



FIGURE 4-7 Map of potential stormwater control projects in the San Marcos area. Stars indicate current water quality logger locations. SOURCE: John Gleason LLC (2017).

## *Comal System*

In the Comal Springs system, both bank restoration and other proposed SCMs have been located near the Old Channel and Landa Lake (Alan Plummer Associates, 2017; Figure 4-8) and approximately $1.1 million in projects have been proposed (Table 4-5). These projects include bioinfiltration strips, rain gardens, rain harvesting in tanks, and underground vaults (one is expected to be completed in the Landa Lake parking lot during reconstruction). Again, design proposals have been evaluated for their capture areas, nutrient reduction, and sediment reduction potentials. Potential sources of funding for these projects are a drainage utility tax and application for funding to the San Antonio River Authority; other grant sources are being investigated. Timetables for implementation are not available. In addition, new development is expected along Blieders Creek (the Veramendi Project) which provides an opportunity to include low-impact development measures rather than merely retrofitting existing urban areas. The WQPP


FIGURE 4-8 Stormwater control measures proposed in New Braunfels near Landa Lake and the Old Channel (north end of map). Stars indicate current water quality logger locations and proposed location on Old Channel. Monitoring location on new channel is off the map. SOURCE: Alan Plummer Associates (2017).

for New Braunfels also proposes limiting development in buffer zones near the streams.

A number of bank stabilization projects have been implemented on Landa Lake by the City of New Braunfels and the Edwards Aquifer Authority, which are discussed in more detail in the section on Riparian Res-

TABLE 4-5 Costs of Proposed Stormwater Control Projects near Landa Lake and the Old Channel

| | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 | Site 6 | Site 7 |
|---|---|---|---|---|---|---|---|
| Location | Elizabeth Ave at Landa Lake | North Union Street from Dallas to Edgewater | North Houston Ave at Landa Lake | Golf Course Club House | Overflow Parking along Elizabeth Ave | Fredericksburg Road Stormdrain Outfall into Landa Park | Landa Park Aquatic Complex Parking Lot |
| **Recommended Measure** | **Rain Garden** | **Linear Roadside Rain Garden** | **Rain Garden** | **Grass/gravel pavers, function as filter strip** | **Grass/gravel pavers** | **Storm Drain Underground Vault** | **Permeable Pavers** |
| **Approx. Drainage Area (acres)** | 5 | 4 | 4.3 | 0.26 | 1.2 | 5.4 | 1.5 |
| **Approx. Impervious Cover (acres)** | 1.9 | 1.2 | 1.3 | 0.24 | 0 | 5 | 1.4 |
| **TSS lbs per year managed** | 875 | 720 | 700 | 170 | 15 | 2200 | 170 |
| **Total Measure Cost** | $71,156 | $138,000 | $99,619 | $34,500 | $138,000 | $86,250 | $345,000 |

NOTE: TSS = total suspended solids.
SOURCE: Alan Plummer Associates (2017) and Pence (2018).

toration. These include rock walls along Landa Lake and vegetative mats, resloping, and fencing along the Old Channel.

### Management of Golf Course Diversions and Operations

These M&M measures are included in the HCP to manage withdrawal of surface water from the Comal River and to improve water quality in the Comal and San Marcos rivers by minimizing runoff of fertilizers and chemicals used on golf courses near the rivers. The City of New Braunfels and Texas State University both committed to developing plans to address fertilizer and chemical use via Integrated Pest Management Plans. Additionally, the City of New Braunfels is allowed to divert water from the Comal River for irrigation, but historically the city has not used its fully permitted amount. The City committed to work with New Braunfels Utilities to develop a water reuse system, and water from this project will be used to supplement or replace water withdrawn from the Comal River.

In 2013, Golf Course Management Plans as well as Integrated Pest Management Plans were developed and implemented for the golf courses in New Braunfels and on the Texas State University Campus (SWCA Environmental Consultants, 2014). The City of New Braunfels maintains a vegetative buffer between the golf course and Landa Lake and the Old Channel of the Comal River to increase protection of water quality. In October 2015 the golf course at Texas State flooded, and several months later university officials decided to close the course. According to an article in the school newspaper (*The University Star*), recreational fields will be developed on the old golf course grounds in the next three to five years. Management of the fields will follow a Grounds Management Plan as well as the previously developed Integrated Pest Management Plan (Blanton and Associates, 2017).

### Litter Collection and Floating Vegetation Management

Reduction of litter and dispersal/removal of floating mats of vegetation is a measure conducted in the Comal and San Marcos systems. Its purpose is to remove/dislodge floating mats of vegetation that accumulate in part from recreational disturbance to vegetation. Litter that has been trapped in the vegetation mats is removed by hand (via SCUBA) prior to dislodging and removal of vegetation mats. Litter is also removed from the bottom of the rivers. Floating mats shade SAV, impede flowering of Texas wild rice, and degrade fountain darter habitat. Focal areas for vegetation mat management include Comal Springs, Landa Lake, the Old and New Channels of the Comal River, and the stretch of the San Marcos River from Sewell Park to interstate highway I-35.

Floating vegetation management and hand removal of litter from both systems is an ongoing process and has been conducted during the entire life of the HCP. This M&M measure is coordinated by the cities of New Braunfels and San Marcos, as well as Texas State University, with each entity responsible for predefined areas. Litter removal peaks in the summer months when recreational use of the rivers is greatest; hundreds of pounds of litter are removed each year (Blanton and Associates, 2016). In 2013, when the City of San Marcos implemented a No Alcohol and No Styrofoam ordinance, there was a reduction in new litter removed by the SCUBA crews (SWCA Environmental Consultants, 2014).

## Will the Water Quality Protection Measures Meet the Water Quality Objective for Fountain Darters?

The Committee's assessment is that the water quality protection M&M measures, focusing primarily on stormwater control, will be **somewhat effective** in meeting the water quality component of the biological objective for fountain darters in the Comal and San Marcos stream systems. This assessment is based on whether the M&M measures, many of which have yet to be implemented, are likely to keep water quality from further degrading or to improve water quality, for whatever parameter they target. Sediment reduction is the target for bank stabilization and other SCMs that control runoff. Nutrient reduction is the target of SCMs that control runoff and golf course management. Organic contaminants are the target of coal tar restrictions, street sweeping, and golf course management. Each of these water quality parameters has the potential to impact fountain darter habitat. The rating is based on the prevailing evidence of the benefits of SCMs in other areas as well as on the plans provided for the Comal and San Marcos systems, rather than existing data for these systems. The Committee believes that the plans for water quality protection, which have been recently updated, are moving in the right direction. The section below discusses the reasons for the rating of **somewhat effective** and makes suggestions for how a higher rating could be achieved.

Two main considerations have led to the rating of somewhat effective. The first is an issue in any urban system: the effectiveness of SCMs for overall stream health is very difficult to assess, and long-term monitoring is needed (STAC, 2010; Hamel et al., 2013). Nonetheless, capturing stormwater is an important strategy to help reduce pollutant loading to the system. The second issue is the high degree of uncertainty in implementation rates, which makes it difficult to assess how much improvement can be expected. The plans list far more projects than the handful that are currently underway, and the EAA has limited opportunity to manage stormwater in the upper portions of the watershed outside their direct control.

Several activities would improve the likelihood of impactful SCMs. First and foremost, there should be formalized project tracking to help with prioritization and assessment of progress. Second, it is critical to track project functioning, including visual inspections. Informal inspection programs have been occurring in some areas, but formal inspection to ensure that all SCMs are functioning and receiving necessary maintenance would help improve success rates. Third, mapping of stormwater capture areas is important and would benefit from ground-based LiDAR surveys for detailed topographic analysis. Many SCMs fail because the capture area is not accurately estimated, and the structure overflows due to underdesign or underperforms due to overdesign. Fourth, performance monitoring of SCMs is needed, but the current water quality monitoring program may not be sufficient to assess effectiveness. For example, the monitoring point in City Park is not at the end of the restoration work along that reach (Figure 4-7). While moving long-term monitoring sites is not recommended, adding new sample sites or additional data loggers could help assess the performance of SCMs, such as the monitoring point being added where Sessom Creek enters the main channel (Figure 4-6). Furthermore, SCMs can be assessed using water-level loggers placed to look for evidence of stormwater capture, bypassing, or overflows (Toran, 2016). Finally, it is important to recognize that benefits of SCMs can be difficult to measure, particularly for water quality parameters. Stabilization of parameters and a reduction in peak flows are also important for improving habitats (e.g., by reducing sediment loading). Population growth in the watershed guarantees that stormwater management will continue to be necessary to maintain water quality in the stream systems.

## SUBMERGED AQUATIC VEGETATION RESTORATION

Restoration and maintenance of SAV is a key component of reaching the biological goals for fountain darters because these fish are strongly dependent on a vegetated habitat. Alongside this specific goal, SAV is widely recognized as an ecologically valuable component of streams and lakes because it supports invertebrates that may be near the base of the food web, and oxygen produced by the plants can help maintain adequate levels of dissolved oxygen. The HCP lays out four M&M measures related to aquatic plants. The first is specific for Texas wild rice *(Zizania texana)*, one of the listed species and also recognized as habitat for fountain darters. The other three M&M measures all deal with some aspect of plant management, including removal of exotic/invasive species and either active planting or maintenance (gardening) of desired native plants that have been documented as fountain darter habitat. These three measures are considered together since the actual management activities are quite similar, although there are reach-specific goals for coverage and differences in the ultimate desired SAV communities in the Comal and San Marcos systems.

SAV species known to support fountain darters at abundances on the order of 5 individuals/$m^2$ or greater are targeted for planting, and explicit areal coverages for each SAV type and reach are based on historical records of plant abundance. These actions are guided by a fundamental assumption that more habitat for the fountain darter will ultimately lead to an overall increase in its population and will probably confer more resilience to negative events, such as low flows or floods. Along with planting native SAV is the active removal of nonnative SAV species (even if known to be fountain darter habitat). Note that removing nonnative SAV without sufficient replacement and restoration of native SAV can result in a net loss of fountain darter habitat, although there is a projected plan to regain lost area with native SAV. In this instance, nonnative SAV removal is largely a management choice related to the preference for a native community of SAV. The exception to this is the potential benefit of nonnative SAV removal to restoration of Texas wild rice, which could be articulated with a new biological objective for Texas wild rice (as discussed in Chapter 3). Table 4-6 gives the HCP reference for each SAV restoration M&M measure, the relevant system, and target species.

### Texas Wild Rice Enhancement and Restoration

Texas wild rice grows only in the upper reaches of the San Marcos River—an indication of how rare this species is. First collected in 1892, Texas wild rice was formally designated as a distinct species in 1933. At

TABLE 4-6 Submerged Aquatic Vegetation Restoration Measures in the Habitat Conservation Plan

| M&M Measure (HCP Section) | Spring System | Target Species |
|---|---|---|
| Texas wild rice enhancement and restoration (5.3.1, 5.4.1) | San Marcos | TWR, FD |
| SAV restoration (nonnative removal and native reestablishment) and maintenance (5.3.8, 5.4.3, 5.4.12) | Comal and San Marcos | TWR, FD |
| Landa Lake and Comal River aquatic vegetation restoration and maintenance (5.2.2) | Comal | FD |
| Old Channel Environmental Restoration and Protection Area (5.2.2.1) | Comal | FD |

NOTE: FD = fountain darter; TWR = Texas wild rice.

that time, Texas wild rice was abundant in the San Marcos River, including Spring Lake (Terrell et al., 1978). By the 1960s, however, there had been several attempts to remove Texas wild rice from the San Marcos River, going so far as to harrow the bottom with agricultural equipment to make the river more enticing for recreational activities. When Emery (1967) observed the length of the San Marcos River, he only found a single specimen in Spring Lake. Furthermore, he observed no Texas wild rice in the uppermost 0.8 km of the San Marcos River, with a few scattered plants in the lower 2.4 km, and none at all were left below this reach. A follow-up estimate by Beaty (1975) revealed a coverage of about 240 $m^2$. In 1976, Emery measured Texas wild rice abundance using a floating frame and found a total cover of 1,131 $m^2$ with most of it in the upper reaches (Emery, 1977). The Texas Parks and Wildlife Department monitored areal coverage of Texas wild rice from June 1989 to 1994, which reveals baseline conditions in the San Marcos River before restoration of about 1,005 $m^2$ to 1,592 $m^2$.

The long-term biological goals (LTBGs) for Texas wild rice (see Table 2-2) are an order of magnitude higher than the low abundances observed in the decades before the HCP. And yet, they have been nearly achieved in total, as shown in Table 4-7, although some reach-specific abundances have not yet reached their targets. Since the last total system sampling of SAV carried out in 2013, Texas wild rice has expanded by an estimated 7,963 $m^2$ through planting and natural expansion. Over the last year alone, Texas wild rice expanded by an estimated 3,800 $m^2$ in the San Marcos River, with every reach having gained coverage, even the reach below I-35. This recovery trend is not only good news for Texas wild rice, but it also aids in reaching the fountain darter biological goals. Expansion of Texas wild rice in the City Park region of the San Marcos River is shown in Figure 4-9.

TABLE 4-7 Progress in Reaching the Biological Goals for Texas Wild Rice in the San Marcos System

| Reach Segment | Area, $m^2$ | Goal, $m^2$ | % Attained |
|---|---|---|---|
| Spring Lake | 41 | 1,000 – 1,500 | 4.1 |
| Spring Lake Dam to Rio Vista | 8,769 | 5,810 – 9,245 | 100 |
| Rio Vista Dam to I-35 | 404 | 910 – 1,650 | 44.4 |
| Downstream of I-35 | 52 | 280 – 3,055 | 18.7 |
| **Total** | **9,266** | **8,000 – 15,450** | **100** |

SOURCE: Furl (2017).

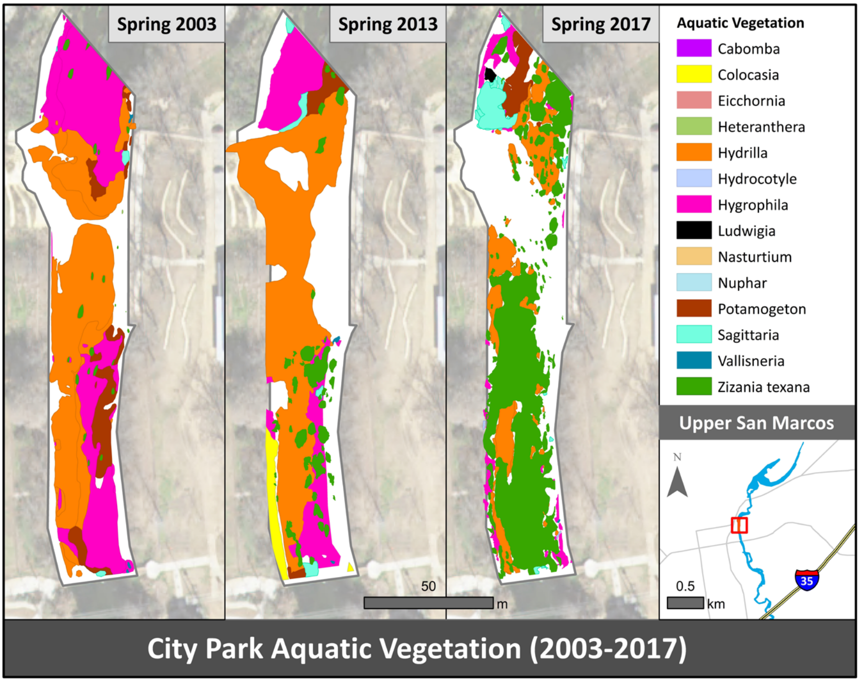



FIGURE 4-9 Progress in the planting and propagation of Texas wild rice *(Zizania)* in the City Park region of the San Marcos River. SOURCE: Furl (2017).

Texas wild rice is monitored along the entire length of the San Marcos River annually.

The Committee hypothesizes that the combined measures of removing nonnatives and replanting native SAV have been particularly important to the success of Texas wild rice because the nonnatives (*Hydrilla* and *Hygrophila*) are all carbon-concentrating species capable of outcompeting Texas wild rice, especially if pH or temperature becomes elevated. It seems clear that nonnative plant removal is one important factor in the 2017 resurgence of Texas wild rice in the San Marcos system. The City of San Marcos's efforts to remove nonnative SAV, plant Texas wild rice, and maintain the newly planted species via gardening appears to be highly successful thus far.

## SAV Restoration and Maintenance

The focus of SAV restoration measures in both the Comal and San Marcos systems has been removal of nonnative species, reestablishment of native species, and conservation or maintenance of native species. These activities are carried out by the cities of New Braunfels and San Marcos and by Texas State University. The primary native SAV species used in reestablishment include *Ludwigia*, *Sagittaria*, *Cabomba*, *Potamogeton*, and *Vallisneria*. Bryophytes are mapped and sampled and support the highest density of fountain darters per area (BIO-WEST, 2016), but they are not subject to active planting. (Bryophytes are relatively small, short-stature, non-flowering plants. Despite their importance, management of these plants is limited to keeping some open space, free of other plants, for their occupation and spread. Active planting of bryophytes is not considered effective because they lack seeds and consequently are difficult to raise, handle, and establish.)

The purpose of these M&M measures has been to increase areal coverage by several species of SAV to serve as habitat for the fountain darter. Indeed, as discussed in Chapter 2, the biological goals for fountain darters in both systems involve maintaining a certain areal coverage of specific native SAV species (see Table 2-1). To make room in the river channels for more native SAV, there has also clearly been a focus on eradicating nonnative SAV species such as *Hydrilla* and *Hygrophila*, even though these nonnatives can support fountain darters. As discussed in NASEM (2017), there can be conflict between the objectives of planting native SAV and removing nonnative SAV when reestablishment of natives does not immediately replace the fountain darter habitat value lost with removal of the nonnative species. This concern was addressed by an adaptive management action taken by the EAA in late 2016 after publication of the SAV report (BIO-WEST and Watershed Systems Group, 2016). The action added new areas subject to native SAV establishment, the so-called restoration reaches, to the existing LTBG reaches where acreage goals were already in force. In addition, the action removed nonnative SAV from the tables of fountain darter biological goals. The revised tables of SAV areal coverage, SAV species, and fountain darter abundance in each type of vegetation reflect the realities of the actual area suitable for SAV growth along with the focus on removal of nonnatives.

Success of these measures has been incremental since implementation of the HCP began, and the reader is referred to the HCP annual reports to see the SAV individual plant numbers and acreage planted in specific years. In 2017, planning in the Comal system focused on the Old Channel area, including the LTBG reach and an adjacent restoration reach as well as Landa Lake. Only limited native SAV planting occurred in the Upper Spring Run

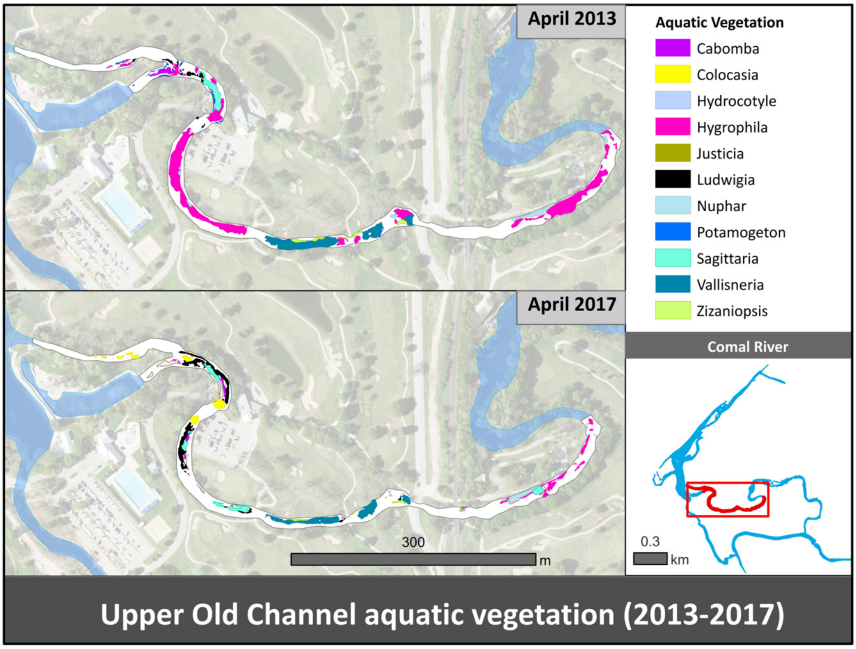



FIGURE 4-10 Changes in the submerged aquatic vegetation of the Upper Old Channel restoration reach from 2013 to 2017. SOURCE: Furl (2017).

LTBG and restoration reaches. In ten areas in the Old Channel LTBG and restoration reaches, 1,433 $m^2$ of native SAV was planted, for a cumulative, five-year total area planted in the Old Channel of 4,814 $m^2$. This acreage corresponds to a total of 6,073 plants. Also in 2017, 502 $m^2$ were planted in eight restoration plots in Landa Lake, bringing the five-year total acreage planted in the lake to 3,429 $m^2$. In terms of nonnative SAV removal, approximately 886 $m^2$ of *Hygrophila* was removed from the Comal River system in 2017.

Figure 4-10 demonstrates that from 2013 to 2017 there has been a substantial shift in the SAV species found in the Old Channel, an area that has undergone extensive removal of nonnative SAV and replanting of native SAV. Table 4-8 shows the 2017 seasonal coverage of various native and nonnative SAV types in both the Old Channel LTBG reach and the Upper Spring Run LTBG reach. As indicated in the table, most native SAV types increased in coverage over the year, both from new plantings following removal of *Hygrophila* and from expansion of existing beds. The table indicates how far the restoration is from reaching the goals for each SAV type in

TABLE 4-8 Seasonal Coverage of Submerged Aquatic Vegetation ($m^2$) in Two Reaches of the Comal System in 2017

| Species | October 2016 | January 2017 | April 2017 | October 2017 | Goal |
|---|---|---|---|---|---|
| Old Channel LTBG Reach | | | | | |
| *Ludwigia* | 35 | 14 | 10 | 106 | 425 |
| *Sagittaria* | 0 | 0 | 0 | 45 | 450 |
| *Cabomba* | 0 | 0 | 0 | 72 | 180 |
| *Hygrophila* | 503 | 818 | 962 | 589 | 0 |
| *Bryophytes* | 250 | 114 | 58 | 107 | 550 |
| Upper Spring Run LTBG Reach | | | | | |
| *Ludwigia* | 53 | 72 | 45 | 21 | 25 |
| *Sagittaria* | 936 | 761 | 982 | 961 | 850 |
| *Cabomba* | 9 | 5 | 7 | 7 | 25 |
| *Hygrophila* | 0 | 0 | 0 | 0 | 0 |
| *Bryophytes* | 1,536 | 1,687 | 1,944 | 1,070 | 1,750 |

NOTE: LTBG = long-term biological goal.
SOURCE: Blanton and Associates (2018; Tables 3.2-3 and 3.2-10).

each reach, with considerably more progress having been made in the Upper Spring Run reach than in the Old Channel reach. Since implementation of the HCP, substantial amounts of nonnatives have been removed, leading to a loss in fountain darter habitat (as discussed in NASEM, 2017), but that habitat is slowly being replaced with native SAV.

As discussed above, the City of San Marcos spends considerable time and resources on the planting of Texas wild rice, which occurs alongside efforts to restore other native SAV that provides superior habitat for the fountain darter in the San Marcos River. In 2017, these measures were focused on certain portions of the river, such as Spring Lake, the Spring Lake Dam LTBG reach, the City Park LTBG reach, the Cypress Island restoration reach, the I-35 LTBG reach, and the expanded I-35 restoration reach. As an example of the progress made, in the Spring Lake Dam LTBG reach, approximately 498 $m^2$ of *Hydrilla*, *Hygrophila*, and vegetation mats were removed. Once the area was denuded of nonnative SAV, an estimated 30 $m^2$ was planted with about 930 individual plants, including *Cabomba* (120 individuals), *Ludwigia* (804 individuals), and *Sagittaria* (10 individuals) (Figure 4-11). As one progresses farther down the river, the removal and replanting efforts diminish, and for many reaches only SAV maintenance has been performed. This was in accordance with the restoration time line enacted after the biological goals for the fountain darter in both systems were updated in late 2016. In total, approximately 3,595 m$^2$ of nonnative SAV were removed from the San Marcos system, and almost 46,000 individuals were planted in 2017 (including Texas wild rice). *Ludwigia repens* was particularly successful in comparison to other species and to past years. There were small increases in acreage for *Cabomba*, but only mixed results for *Potamogeton*.

In both the Comal and San Marcos systems, progress toward reaching the SAV acreage goals has been incremental, with both losses and gains being experienced since implementation of the HCP. This may not be apparent from Figures 4-10 and 4-11 but is exemplified in Tables 4-9 and 4-10. These tables show that while removal of the nonnative *Hydrilla* and *Hygrophila* from the San Marcos system has been consistent and successful in terms of acreage removed from 2013 to 2016, the planting of native SAV has not kept pace, and in some cases there has been a net negative acreage (e.g., with *Potamogeton* and *Cabomba*). Looking forward, there are plans for continued planting of native SAV that appear feasible and capable of

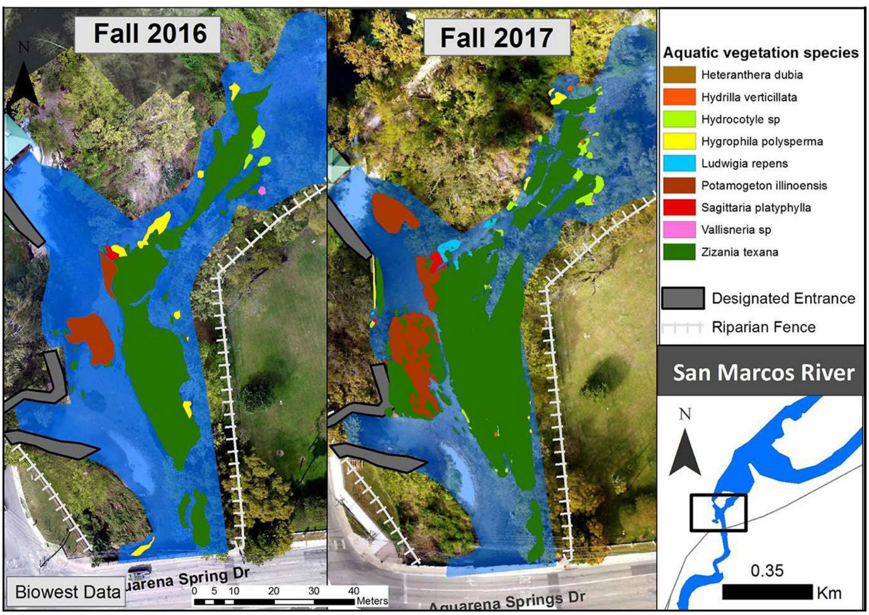



FIGURE 4-11 Changes in aquatic vegetation within the Spring Lake Dam LTBG reach of the San Marcos River from fall 2016 to fall 2017. Texas wild rice is *Zizania*. SOURCE: Blanton and Associates (2018).

TABLE 4-9 Trends in Areal Coverage ($m^2$) of Aquatic Vegetation at all San Marcos Work Sites from 2013 to 2016 and Changes Detected 2013–2016 and 2015–2016

| Species | 2013 | 2014 | 2015 | 2016 | 2013–2016 | 2015–2016 |
|---|---|---|---|---|---|---|
| *Cabomba* | 163.0 | 36.6 | 13.8 | 11.5 | –151.5 | –2.3 |
| *Heteranthera* | 0.0 | 152.8 | 63.8 | 165.5 | 165.5 | 101.7 |
| *Hydrilla*[a] | 3,980.2 | 1,804.1 | 1,032.5 | 864.1 | –3,116.1 | –168.4 |
| *Hydrocotyle* | 78.2 | 131.4 | 25.3 | 112.4 | 34.2 | 87.1 |
| *Hygrophila*[a] | 2,610.6 | 1,382.6 | 888.8 | 861.6 | –1,749.0 | –27.2 |
| *Ludwigia* | 0.0 | 73.3 | 0.0 | 9.0 | 9.0 | 9.0 |
| *Nasturtium*[a] | 31.4 | 111.7 | 0.0 | 0.0 | –31.4 | 0.0 |
| *Potamogeton* | 1,530.4 | 762.7 | 437.8 | 800.9 | –729.5 | 363.1 |

[a]Nonnative species. Work sites in 2016 had aquatic vegetation efforts (i.e., removal and planting) and included Spring Lake, Sewell Park, City Park, Hopkins Street–Bicentennial Park, Cypress Island, Rio-Vista Dam, and I-35.
SOURCE: Blanton and Associates (2017).

TABLE 4-10 Trends in Areal Coverage ($m^2$) of Aquatic Vegetation at City Park of San Marcos River 2013–2016 and Changes Detected 2013–2016 and 2015–2016

| **Species** | **2013** | **2015** | **2016** | **2013–2016** | **2015–2016** |
|---|---|---|---|---|---|
| *Heteranthera* | 0.0 | 0.3 | 0.8 | 0.8 | 0.5 |
| *Hydrilla*[a] | 1,466.3 | 308.3 | 301.1 | –1,165.2 | –7.2 |
| *Hydrocotyle* | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 |
| *Hygrophila*[a] | 585.6 | 191.8 | 53.8 | –531.8 | –138.0 |
| *Ludwigia* | 0.0 | 0.0 | 9.0 | 9.0 | 9.0 |
| *Nasturtium*[a] | 1.6 | 0.0 | 0.0 | –1.6 | 0.0 |
| *Potamogeton* | 254.0 | 180.2 | 112.1 | –141.9 | –68.1 |
| *Sagittaria* | 17.8 | 0.0 | 19.1 | 1.3 | 19.1 |
| *Vallisneria*[a] | 1.7 | 0.0 | 0.0 | –1.7 | 0.0 |
| *Zizania* | 384.3 | 1,348.3 | 1,544.6 | 1,160.3 | 196.3 |

[a]Nonnative species.
SOURCE: Blanton and Associates (2017).

reaching the coverage targets. Tables 26 (Comal) and 34 (San Marcos) in BIO-WEST and Watershed Systems Group (2016) show year-by-year efforts required to attain the required areal coverage. Planting of roughly 12 to 50 of each species in each reach will attain the coverage goal, and the contractors have shown the capacity and knowledge required to carry out this work.

As discussed in detail in the Committee's second report (NASEM, 2017), the Comal and San Marcos SAV teams have had considerable success in terms of the ratio of plants put in the system that have survived and become established. As of 2016, the ratios of individual plants to resulting coverage in square meters was 20:1 in the Comal and 31:1 in the San Marcos (BIO-WEST and Watershed Systems Group, 2016). The Texas wild rice ratio was eight plants for every resulting square meter of coverage. Extensive experience by the contractors has added to confidence in propagation and planting methodologies such that a restoration plan describing the required area of new SAV along with a time line for achieving the coverage goals appears reasonable for both systems, with work in the Comal system scheduled for completion by 2023 and in the San Marcos system by 2027. Areas to be planted and maintained in each year are within the amount of yearly work already performed (although the work is expensive and increases would easily exceed budgeted amounts).

The monitoring of SAV in the two river systems is extensive. As discussed in previous reports of the Committee, aquatic vegetation is mapped throughout the entire river systems every five years, although in the San Marcos River, Texas wild rice is mapped annually. Vegetation in the LTBG reaches is mapped twice per year and when triggered by low-flow conditions. This monitoring program means that there are abundant data for performance monitoring of the restoration measures, as exemplified by BIO-WEST and Watershed Systems Group (2016), which included the number of plants planted, resulting sustained area, increased coverage of vegetation from baseline maps in 2013, and lessons learned from new techniques.

As discussed extensively in NASEM (2017), a mechanistic model of SAV growth and dispersal was constructed as part of the larger ecomodel developed for the fountain darter. The model development was useful because it highlighted the factors presumed to affect SAV performance, such as interspecific competition for light, sensitivity to flow velocities, nutrient limitation, or substrate preference. Unfortunately, model development has not reached the point where the model can be used to predict the performance of the SAV restoration measures.

### Will the SAV Restoration Measures Meet the Habitat Objectives for Texas Wild Rice and the Fountain Darter?

With their documented success in planting and propagation to date, removal of nonnative SAV, and readjustment of SAV species included as fountain darter habitat, the Committee determines that these combined measures will be **effective** in meeting the habitat component of the biological goals for Texas wild rice and the fountain darter. These measures were not rated as highly effective for three main reasons. First, there may be a scouring flood that could completely reset both systems (although this is largely outside human control). Over geological time, the systems have certainly been scoured multiple times and recovered, but with climate change, such events may be more common in the future. Second, for the Comal system there is a reliance on bryophyte cover to provide habitat for about 75 percent of the fountain darters. Bryophytes cannot be actively managed, and the present strategy is simply to maintain some open areas suitable for bryophytes and free of both native and nonnative plants. This is an overreliance on the capability of these plants to spread and establish without a solid understanding of what controls bryophyte success. In addition, there is not a clear management response to be brought to bear if naturally recruited bryophyte coverage seems to be falling short of the required area. Finally, continual maintenance gardening will be needed to meet the SAV targets in both systems. Financial constraints may arise from the maintenance needs of existing SAV if extreme events occur or if progressively inferior portions of the rivers are targeted for planting. The Committee understands that there is a cushion of restoration funds now, but there is no guarantee that this will be sufficient for the "perfect storm" of bad events or that the funds will remain available indefinitely.

The current practice of brute-force weeding and planting will probably allow the EAA to meet its objectives but may not be sustainable, and the resulting systems may not be as resilient as a system that sorts itself out with different coverages of various SAV species. Separately, it seems likely that removal of nonnative SAV is key to further expansion of Texas wild rice. As discussed further in Chapter 5, it would be desirable to have the systems become more self-maintaining.

## RECREATION MANAGEMENT

Human recreational use of the San Marcos and Comal systems has occurred for decades, and continued recreational use of these natural resources is identified as one of the activities covered by the HCP. Recreational use of the springs and associated river stretches is under the jurisdiction of the cities of New Braunfels and San Marcos, as well as Texas State University. These entities played a large role in developing the recreational M&M measures, along with individuals representing recreational interests. The EAA also contracted with Halff Associates to prepare a Recreation Study that reviewed and summarized existing data and ordinances that regulate recreation and recreation development in the San Marcos and Comal systems (Halff Associates, Inc., 2010). Findings from this study, stakeholder comments, deliberations among members of the Recreation Work Group, as well as input from the five HCP permit holders were instrumental in developing M&M measures to reduce or eliminate negative impacts to the Comal and San Marcos systems from recreational activities of the hundreds of thousands of people who enjoy these natural resources each year.

The majority of recreation-associated M&M measures target habitat protection and water quality issues such as siltation and turbidity. Protections to mitigate recreation-associated damage to covered species are often most important during periods of low flow. More recreation-associated M&M measures were identified in the HCP for the San Marcos system than for the Comal, largely due to recreational activities associated with Sewell Park on the Texas State University campus, the tubing operation at City Park, and other recreational activities (swimming, fishing, picnicking, etc.) that occur at public recreation areas downstream to I-35. The recreational M&M measures listed in the HCP are outlined in Table 4-11.

TABLE 4-11 Recreation Management Measures in the Habitat Conservation Plan

| M&M Measure (HCP Section) | Spring System | Target Species[a] | Purpose |
|---|---|---|---|
| Management of public recreational use (5.2.3) | Comal | CSRB, FD | Prevent physical damage to species and their habitats |
| Management of recreation in key areas (5.3.2, 5.3.2.1, 5.4.2) | San Marcos | TWR, FD | Reduce physical damage to TWR |
| Designation of permanent access points/bank stabilization (5.3.7) | San Marcos | TWR | Prevent shoreline erosion |
| Diving classes in Spring Lake (5.4.7.1, 5.4.7.2, 5.4.7.3) | San Marcos | SMS, FD, TWR | Prevent physical damage to species and their habitats |
| Boating in Spring Lake and Sewell Park (5.4.10) | San Marcos | SMS, FD, TWR | Prevent physical damage to species and their habitats |
| State Scientific Areas (5.6.1) | San Marcos | TWR | Prevent physical damage to species and their habitats |

NOTE: CSRB = Comal Springs riffle beetle, FD= fountain darter; SMS = San Marcos salamander; TWR = Texas wild rice.
[a]This column is broader than those species that have a district recreational control biological objective. Rather, it broadly considers all organisms that could benefit from recreational control.

### Management of Public Recreational Use in the Comal System

Recreational use of the Comal system is addressed via two strategies: (1) New Braunfels City ordinances and policies and (2) issue of Certificates of Inclusion (COIs) for commercial outfitters that desire coverage under the incidental take permit (ITP). The City of New Braunfels made the commitment not to relax environmental protections to the Comal system that were already provided when the HCP was written. They also agreed to enforce current regulations, limit recreational use on Landa Lake to paddle boats, prohibit access to spring runs in Landa Park to just the wading pool of Spring Run 2, and prohibit recreation in the Old Channel, with the exception of recreational activities associated with the Schlitterbahn Waterpark Resort. The City also committed to develop a COI program for recreational outfitters (e.g., mainly inner-tube providers) that follows certain guidelines (e.g., provide litter bags, organize an annual river cleanup, erect educational signage, submit an annual report). Outfitters that opt in to this voluntary program and adhere to all its requirements receive incidental take coverage of listed species in the HCP for the duration of their certificate (not to exceed the duration of the ITP term).

The City of New Braunfels continues to enforce City Ordinance Section 142-5, which restricts access to Landa Lake, Comal Spring runs, and the Old Channel of the Comal River, as they are obligated to do under the HCP. Enforcement began the first year the HCP was in effect and has been ongoing. Signs were installed near the shoreline at Landa Lake and spring runs informing visitors about this environmentally sensitive area and access restrictions. These efforts may have questionable effectiveness, as during a Committee site visit in October 2017, several park visitors were observed wading in one of the protected spring runs.

The recreational outfitter COI program was initiated the first year of the HCP. The goal for 2014 was to enroll most of the outfitters by the end of that year. Nonetheless, the HCP annual report for 2016 states that the City of New Braunfels reported that this process is still ongoing, and outfitters continue to be recruited to join the COI program (Blanton and Associates, 2017). However, as of January 2018, *no* recreational outfitters have enrolled in the program. Outfitters not enrolled in the program remain liable for take of listed species due to their operations. Enrollment of all outfitters in this program should be pursued to reduce recreational impacts, enhance public awareness, and alleviate liability of outfitters through coverage under the ITP.

### Management of Recreation in the San Marcos System, Including the Designation of Permanent Access Points/Bank Stabilization

Recreational M&M measures in the San Marcos system involve protecting Texas wild rice in the San Marcos River from damage caused by a diversity of activities (e.g., swimming, snorkeling/SCUBA, tubing, and recreation with dogs). Protecting fountain darters from increased turbidity (caused by shoreline erosion) and incidental contact by recreationists is another important goal. The recreation area of greatest concern in the San Marcos River is at City Park, where there is high demand for inner tubes rented by the Lion's Club operating out of the San Marcos City Recreation Hall. Additional key recreation areas targeted in the HCP include Spring Lake and access points along the river on the Texas State University campus. "Recreation control is not meant to curtail recreation for large stretches of the river, but simply within key high quality habitat areas for Texas wild rice to limit unnecessary impacts during low-flow conditions." (EARIP, 2012).

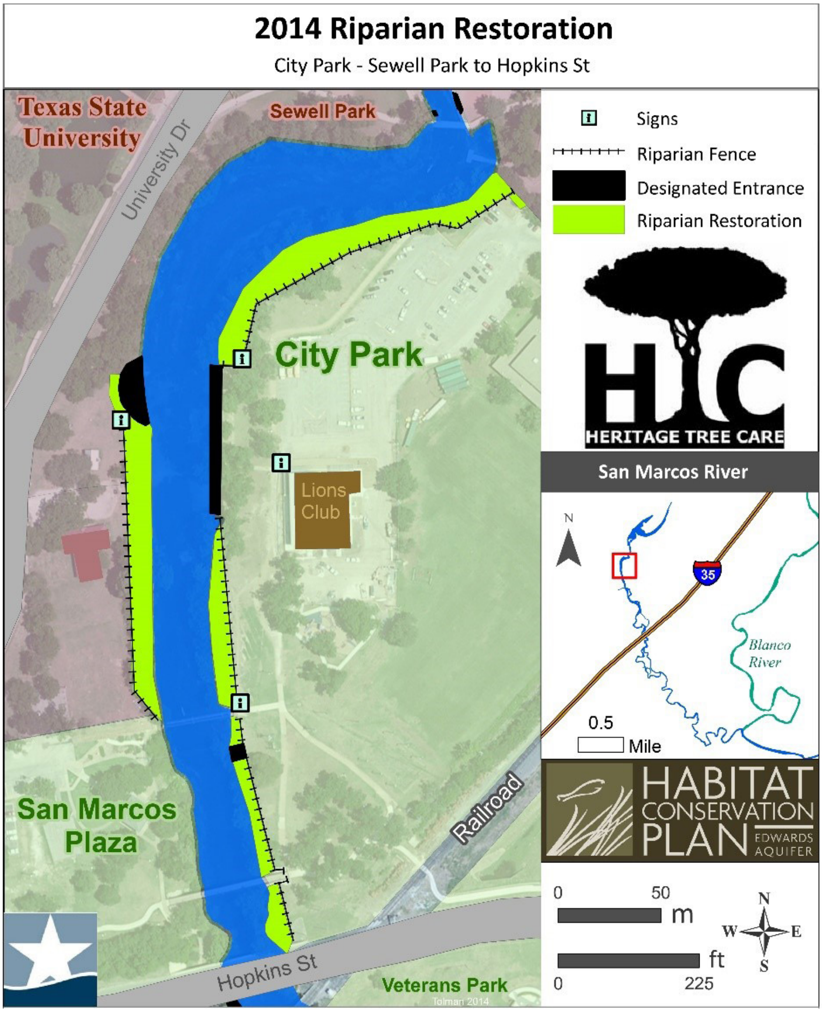



FIGURE 4-12 Location of designated access points including bank stabilization, riparian restoration, and fencing along City Park. SOURCE: Blanton and Associates (2015).

A specific recreational M&M measure was for the City of San Marcos to establish permanent river-access points at several locations along the San Marcos River: City Park (see the black areas in Figure 4-12), Hopkins Street and Cheatham Street underpasses, Bicentennial Park, Rio Vista Park (Figure 4-13), and Ramon Lucio Park (Figure 4-14). These sites were chosen because they were already being used by recreationists to access the San Marcos River and were heavily eroded. Texas State University was

FIGURE 4-13 Access point under construction at Rio Vista Park. SOURCE: Blanton and Associates (2015).

FIGURE 4-14 Lower Ramon Lucio Park access point. SOURCE: Blanton and Associates (2015).

also tasked to establish permanent river-access points on the east and west banks of the river between Spring Lake Dam and the bridge at Aquarena Drive. Additional permanent access points include Dog Beach, Lion's Club Tube Rental, the Wildlife Annex, and possibly other areas over time. The establishment of permanent access points (via the installation of hardened structures) directs river users to desired locations and also stabilizes the bank from erosion and reduces turbidity.

Areas of riverbank interspersed among the permanent access points are to be planted with dense vegetation to encourage river access only at desired locations. The City of San Marcos also committed to work with private landowners to enforce trespassing laws because the public uses private property illegally to gain access to the river. An educational program was proposed in the HCP that includes signage erected at the access points, maps showing locations of access points, literature distributed at local businesses, and an outreach program for the San Marcos Consolidated Independent School District, among other educational tools. The City of San Marcos and Texas State University also agreed to a partnership to educate river users and enforce environmental regulations. Finally, like the City of New Braunfels, the City of San Marcos was to implement a recreational outfitter COI program as described earlier.

Establishment of permanent river-access points at all predetermined locations was completed by the end of 2014 (Blanton and Associates, 2015), and the City of San Marcos has maintained the access points and repaired bank stabilization structures as needed since then. Terraces and walls were constructed from natural stone to stabilize the riverbank and facilitate river access by the public. Native vegetation was planted between permanent access points to eliminate public access in these areas. Fences were erected at the upland edge of the plantings to protect the vegetation until it matures. Buffer zones (100 ft wide) excluding picnic tables, portable grills, and pop-up shelters from the shore of the San Marcos River were established at Rio Vista Falls and numerous other locations from Sewell Park to I-35. The educational program is in place and continues to realize numerous accomplishments (Blanton and Associates, 2015). Numerous kiosks and educational signs were developed and installed at key recreation areas. In collaboration with Texas State University, a Conservation Crew consisting of a team of university students was developed to educate the public about the HCP, with an emphasis on protected species, especially Texas wild rice. The Conservation Crew is active on the river annually from around Memorial Day to Labor Day. They conduct a variety of activities that include speaking with people along the river about natural resource protection, inspecting riparian fences and educational signs for damage, clearing floating mats of vegetation from Texas wild rice stands, public outreach events, and litter removal—they remove thousands of pounds of litter annually.

The Conservation Crew has become a popular paid-internship opportunity for Texas State University students.

**Diving Classes in Spring Lake**

The purpose of these recreational M&M measures is to ensure that listed species and their habitats within Spring Lake are not negatively impacted by the activities of SCUBA divers in Spring Lake. The Meadows Center for Water and the Environment, operated by Texas State University, is the organization that controls access to and regulates diving in Spring Lake, as specified in the Meadows Center's revised Spring Lake Management Plan. This is accomplished by limiting the number of divers in the lake at any particular time and also ensuring that divers are trained to avoid contacting covered species or disturbing critical habitat. Divers trained under this program provide valuable volunteer services, such as litter removal and algae control. A diving supervisor coordinates and supervises all volunteer divers in Spring Lake. The center has a Diving Program Control Board to review diving activities in Spring Lake to ensure that they are in compliance with the HCP and the Spring Lake Management Plan.

The number of divers using Spring Lake is monitored and reported annually in the HCP annual reports. The Texas State SCUBA Class program was supposed to formally revise their diving classes in 2013 to be consistent with protocols identified in the HCP, but they apparently did not (SWCA Environmental Consultants, 2014). However, in 2016 Texas State formally adopted the recreational diving protocol outlined in the HCP and the Spring Lake Management Plan.

**Boating in Spring Lake and Sewell Park**

Boating activities in Spring Lake and Sewell Park are regulated to minimize impacts to covered species and their habitats in the lake and in the San Marcos River. Boating M&M measures include limiting the number of boats on the water as well as designating access points and the areas where boats are allowed to operate (covered vessels include canoes, kayaks, and glass-bottom boats). Additionally, all boats launched at Spring Lake are cleaned before launching, following a protocol approved by the U.S. Fish and Wildlife Service (FWS).

In 2013, the Meadows Center revised its Spring Lake Management Plan to include measures outlined in the HCP. In Spring Lake these include limiting canoe and kayak classes to ≤ 2 classes/day that are limited to 20 students in 10 boats, and with a maximum time on the water of one hour; restricting operation of glass-bottom boats to areas of Spring Lake that are "mowed" with a harvester to control aquatic vegetation; decontamination of all boats launched at the lake following an approved protocol; and launching of boats only at established locations. At Sewell Park, canoe and kayak classes are limited to the stretch of the San Marcos River between the park and the Rio Vista dam. Boat access is limited to the floating dock adjacent to the recreation center. Additional restrictions include no more than three classes/day (each with a maximum duration of two hours) with 20 or fewer students in no more than ten boats. Texas State University was supposed to formally modify its boating program at Spring Lake and Sewell Park to be consistent with these guidelines in 2013 (SWCA Environmental Consultants, 2014), but apparently did not do so until 2015 (Blanton and Associates, 2016).

### State Scientific Areas

Recreational activities traditionally occurring on the San Marcos and Comal Rivers (e.g., swimming, snorkeling, boating, tubing, wading, fishing, and dog activity) can have negative impacts on habitat for covered species. These impacts are exacerbated at low flows, when a greater percentage of plants and bottom substrate is exposed to potential negative consequences. The Texas Parks and Wildlife Department (TPWD) has the authority to establish State Scientific Areas (SSAs) for the purposes of education, scientific research, and preservation of flora and fauna of scientific or educational value. On March 29, 2012, the TPWD created an SSA designed to protect prime Texas wild rice habitat by restricting recreational activities during flows below 120 cfs in a two-mile reach of the San Marcos River from the Spring Lake Dam to the San Marcos wastewater treatment plant. When flows within the San Marcos River SSA are 120 cfs or less, physical barriers may be placed within the SSA to help recreational users avoid vulnerable stands of Texas wild rice while enjoying the river and to protect areas where habitat has been restored. Rules prohibit moving or altering SSA boundary markers, uprooting Texas wild rice within the area, or entering a marked SSA area. The regulations are intended to preserve at least 1,000 $m^2$ of Texas wild rice.

When flows dropped below 120 cfs in the summer of 2013, physical barriers were deployed around two vulnerable stands of Texas wild rice (at Bicentennial Park and at the eastern spillway) to help people avoid the plant while recreating in the river (Figure 4-15). During summer 2014, flows were again below 120 cfs, and two additional exclusion areas were established downstream of the Hopkins Street railroad bridge and across from the Texas State Outdoor Recreation Center boat dock. Flows remained above 120 cfs in 2015 and 2016. In 2016 the four exclusion areas (see Figure 4-16) encompassed 1,772 $m^2$ of Texas wild rice.

With the exception of the eastern spillway immediately below Spring

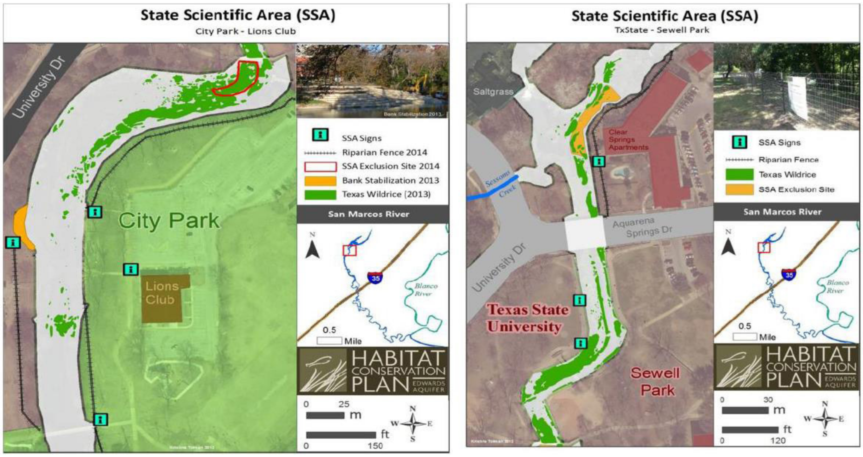
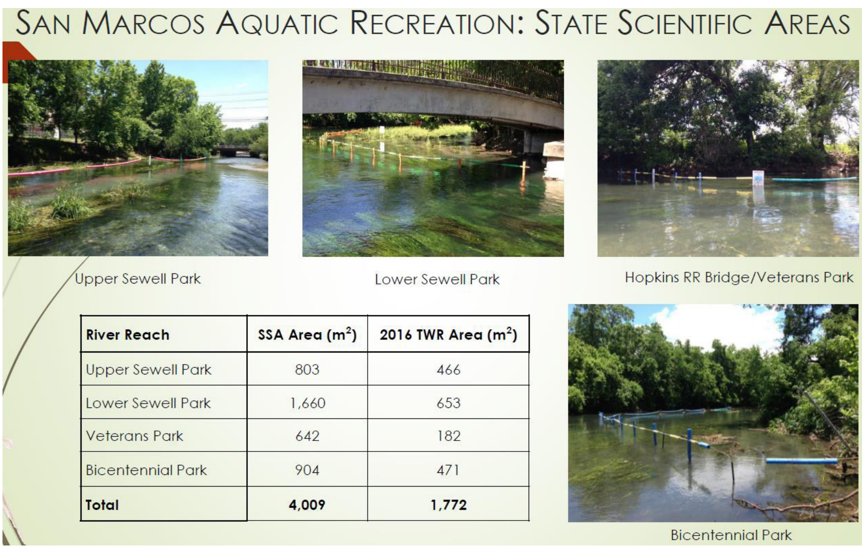



FIGURE 4-15 Location of State Scientific Areas, kiosks, and signage along the San Marcos River. SOURCE: SWCA Environmental Consultants (2014; Fig. 3-22).




| River Reach | SSA Area (m$^2$) | 2016 TWR Area (m$^2$) |
|---|---|---|
| Upper Sewell Park | 803 | 466 |
| Lower Sewell Park | 1,660 | 653 |
| Veterans Park | 642 | 182 |
| Bicentennial Park | 904 | 471 |
| **Total** | **4,009** | **1,772** |

FIGURE 4-16 The four State Scientific Area exclusion areas, their size, and the extent of Texas wild rice included. SOURCE: Furl (2017).

Lake Dam, areas protected by the SSA do not extend across the entire river channel, in order to maintain longitudinal connectivity for recreation and access throughout the river. Under low-flow conditions, recreational access to the eastern spillway is prohibited to protect critical habitat for San Marcos salamanders and to enhance the protection of fountain darters and Texas wild rice in the reach immediately below Spring Lake Dam.

The HCP calls for the TPWD to pursue creation of similar SSAs in the Comal Springs ecosystem to minimize impacts of recreational activities at low flows on existing fountain darter habitat and additional habitat created by the City of New Braunfels. In 2017, the TPWD was to initiate discussions with the City of New Braunfels regarding creation of an SSA for the Comal River.

Recreational use outfitters on the San Marcos system are required to provide a map and educational signage at the point of purchase to inform users about the SSA. A similar requirement will be implemented for outfitters in the Comal system when an SSA is established there.

### Will Recreation Management Lead to Achievement of Texas Wild Rice and San Marcos Salamander Biological Objectives?

The M&M measures associated with recreation management play an important role in meeting several key biological objectives in the HCP, particularly those pertaining to Texas wild rice and the San Marcos salamander. Texas wild rice is directly vulnerable to damage such as breakage, loss of seed heads, and uprooting due to incidental or intentional contact from humans and dogs during in-stream recreational activities, especially during low flows. These impacts can be exacerbated by fragmentation of other vegetation, which then floats downstream and collects on wild-rice stands. Accidental contact by recreationists is less likely for other covered species, but indirect effects on habitat via siltation and turbidity can be important, especially for the San Marcos salamander and the Comal Springs riffle beetle. Recreation management indirectly supports biological objectives for the fountain darter by protecting aquatic vegetation that constitutes critical habitat for them, and by reducing turbidity, which may inhibit feeding by this visual predator.

The Committee rates the M&M measures intended to minimize recreational impact on Texas wild rice and the San Marcos salamander as **effective.** Anecdotal evidence suggests that measures to protect Texas wild rice in the San Marcos system have had favorable results. The suite of onsite and community educational efforts that have been implemented seem to have had a positive impact on user behavior (however, no formal evaluation has been conducted), contributing to successful establishment and maintenance of Texas wild rice stands. Implementation of access restrictions within the

SSA substantially reduced physical disturbance of vulnerable stands during low flows in 2013 and 2014. Establishment of permanent, non-erosive access points, coupled with establishment of riparian vegetation buffers that discourage access elsewhere, has substantially reduced point sources of sedimentation from shoreline erosion. The highly regulated use of boating and diving in Spring Lake not only minimizes impacts on covered species and their habitats but also educates users, promotes awareness, and enhances public appreciation of the San Marcos system. While the COI program for recreational outfitters has the potential to further reduce recreational impacts and enhance public awareness, as of January 2018 *no* outfitters had entered the program.

Considering the limited distribution of San Marcos salamanders and their strong association with spring outflows in Spring Lake, marginally regulated recreational activities, such as tubing, wading, and swimming (which primarily occur in the river proper), have much less potential to impact this listed species as compared to Texas wild rice. Rather, the recreation-associated M&M measures in the HCP that regulate recreation in Spring Lake are intended to prevent physical disturbance of San Marcos salamanders and their benthic habitats. Numerous measures are in place to ensure that SCUBA divers avoid contact with San Marcos salamanders, and only trained divers are allowed to swim outside of the Diver Training Area. These volunteers play an important role in removal of algae and litter from Spring Lake. Boating in Spring Lake is also highly regulated, and specific M&M measures ensure that boats do not damage San Marcos salamanders or their habitats.

There are several actions that can be taken to shift the rating toward highly effective. For Texas wild rice, enrollment of all outfitters in the COI program should be vigorously pursued to further reduce recreational impacts, enhance public awareness, and alleviate liability of outfitters through coverage under the ITP. Education efforts to encourage protection of covered species and their habitat could be further enhanced through the use of social media (e.g., Twitter, Facebook, and Snapchat), and through university websites to reach the campus community at Texas State University. For the San Marcos salamander, recreational access to the 50-meter stream reach immediately below the spillway should be further restricted. For both species it will be important that the actions currently in place be sustained, enforced, and monitored.

## RIPARIAN MANAGEMENT

Riparian management measures, including restoring native riparian vegetation, stabilizing riparian banks, and preventing shoreline erosion and sedimentation, are considered critical to the CSRB, for which one of the biological objectives is to "restore riparian habitat adjacent to spring openings to reduce siltation" (EARIP, 2012). For the San Marcos salamander, there is no explicit biological objective linked to riparian restoration. However, the Committee has inferred its importance given that the biological goals of maintaining silt-free gravel for the salamander and the CSRB are very similar. Furthermore, the HCP states that "From a habitat perspective, the goal [for the San Marcos salamander] is to maintain silt-free habitat conditions via continued spring flow, riparian zone protection, and recreation control throughout each of the three reaches (hotel area, riverbed area, and eastern spillway below Spring Lake Dam)" (EARIP, 2012, p. 4-31).

Well-executed and monitored riparian management activities may also have positive effects on other listed species, for example, by mediating sediment loading and transport in the San Marcos system and thereby affecting the survival of Texas wild rice or by controlling the amount of shading or sedimentation, which can affect the growth of native SAV in both systems. Riparian management also supports recreation management by blocking access to portions of the rivers and funneling people to specific access points. This section focuses on the measures that involve restoring native riparian plant species and stabilizing banks. In the Comal system, this has been primarily, but not exclusively, for the benefit of the CSRB, while in the San Marcos system, riparian management has primarily occurred in conjunction with the establishment of permanent access points (which were evaluated in the Recreation Management section of this chapter). The riparian-related management measures in the HCP are shown in Table 4-12.

### Riparian Restoration in the Comal System for the CSRB

The riparian management measures that predominantly affect whether the biological objectives of the CSRB can be met are those implemented in the LTBG reaches of Comal Springs that are monitored for the CSRB. The LTBG reaches for the CSRB are fed by multiple spring outflows within the reach of each main spring and receive no direct surface flow from upstream, or in the case of the western shoreline of Landa Lake, the springs are immediately adjacent to the bank in areas of low flow. Because of this hydrological disconnect from the main Comal system (e.g., Landa Lake flow), any activities that would impact the monitored CSRB populations will primarily come from the riparian banks immediately adjacent to each spring reach. A primary goal of riparian restoration is to promote bank stabilization by establishing root structures and thus preventing the siltation of adjacent spring openings. A secondary process of importance is the influence of riparian areas on nutrient loading to the aquatic habitat of the CSRB.

A riparian restoration program was implemented in 2013 to improve CSRB habitat in Spring Run 3 and the western shoreline of Landa Lake.

TABLE 4-12 Riparian Management Measures in the Habitat Conservation Plan

| M&M Measure (HCP Section) | Spring System | Target Species | Purpose |
|---|---|---|---|
| Riparian improvements and sediment removal specific to the CSRB (5.2.8) | Comal | CSRB | Increase the amount of usable habitat and food sources |
| Restoration of riparian zone with native vegetation (5.7.1) | Comal and San Marcos | CSRB, SMS, FD, TWR | Prevent shoreline erosion and sedimentation of rivers, provide food source for invertebrates |
| Bank stabilization/ permanent access points (5.3.7) | San Marcos | FD, TWR | Discourage river users from entering the river in places other than permanent access points. |

NOTE: CSRB = Comal Springs riffle beetle; FD = fountain darter; SMS = San Marcos salamander; TWR = Texas wild rice.

These riparian areas are dominated by rocky soils with limited water capacity, shallow bedrock, and limestone outcrops on 20- to 40-percent grades. The overstory is dense and provides considerable shade that affects understory plant growth, which may affect restoration efforts of reestablishing native species. There is also evidence of sizeable deer grazing pressure on the vegetation of this shoreline habitat, in addition to other wildlife and park visitors that physically disturb replanted vegetation and contribute to erosion. Given the steep gradient, low water capacity, shallow rooting zone, and physical disturbance, determining the success of riparian restoration efforts is challenging and has been based primarily on observational evidence.

In 2016, riparian restoration involved (1) removal and/or treatment of exotic vegetation, (2) construction and maintenance of erosion structures, (3) revegetation of the shoreline by planting native vegetation, and (4) sediment and vegetation monitoring. The removal of nonnative vegetation and replanting with native species occurred about 45 feet up the hillside along approximately 1,105 ft of shoreline that extends from Spring Run 3 to private property along the western shoreline of Landa Lake. Temporary infrastructure in the form of drip irrigation lines, erosion control structures, and signs were installed and maintained to help replanted vegetation thrive, reduce sediment movement, and maintain soil moisture. Replanting was primarily with plugs of inland sea oats (*Chasmanthium latifolium*) and Indiangrass (*Sorghastrum nutans*) that had been successfully used in the past, with some seedlings of Mexican buckeye (*Ungnadia speciosa*) and grass plugs. Restoration activities also involved the removal or herbicidal treatment of nonnative species, such as Japanese ligustum (*Ligustrum japonicum*) and elephant ear (*Colocasia* sp.). Plant survival within the restoration area was monitored monthly for a year, while any reemergent nonnative plants were continually removed. In general, the activities have resulted in increased abundance and diversity of the shrub and herbaceous layers (Blanton and Associates, 2017, App. L4).

To prevent bank erosion and runoff into the springs, erosion control structures that range from 3 to 64 ft long were installed along the 1,105 ft of shoreline of the restoration area; these have been maintained and monitored since installation. Sediment capture depth was measured by change in the exposure length of steel pins driven into the sediment within the structures. Captured sediment runoff volume was quantified by measuring sediment accumulation behind the structures. It was estimated that 0.72 cubic yards of sediment was prevented from entering the two study reaches in 2016 (Blanton and Associates, 2017, App. L4).

To prevent physical damage and disturbance to the restoration activities from park visitors, signs were placed along trails and entrances to areas along the restored shoreline. However, the success of this signage is ambiguous, as evidenced by damaged infrastructure. Visual observations by the Committee during a site visit in 2017 found that people were actively wading in and around the spring openings in the presence of signage.

The main negative influence on the riparian restoration activities was excessive rainfall, which submerged or washed out previously planted native species. Areas of the restored shoreline with abundant sunlight supported the most successful replanting efforts, while shaded habitat led to low survivorship of even species considered to be shade tolerant (e.g., certain grasses and wild rye [*Elymus* sp.]). One exception was the ice plant (*Verbesina virginica*) and inland sea oats that are reproducing in the restored shoreline even in shaded areas. In one quantitative survey of inland sea oats, Indiangrass and cut rice grass, the average survivorship of plant plugs in 2016 was 70 percent—higher than in 2013 (36 percent) and 2014 (60 percent), but lower than in 2015 (82 percent), indicating annual variability that should be considered in long-term monitoring. Wild rye showed limited survivorship during summer monitoring events.

In 2017, all of these riparian restoration activities continued along Spring Run 3 and the western shoreline (Figure 4-17). An additional 500 linear feet of brush berms and fenced enclosures were constructed in 2017 to prevent deer foraging and trampling of replanted native vegetation and

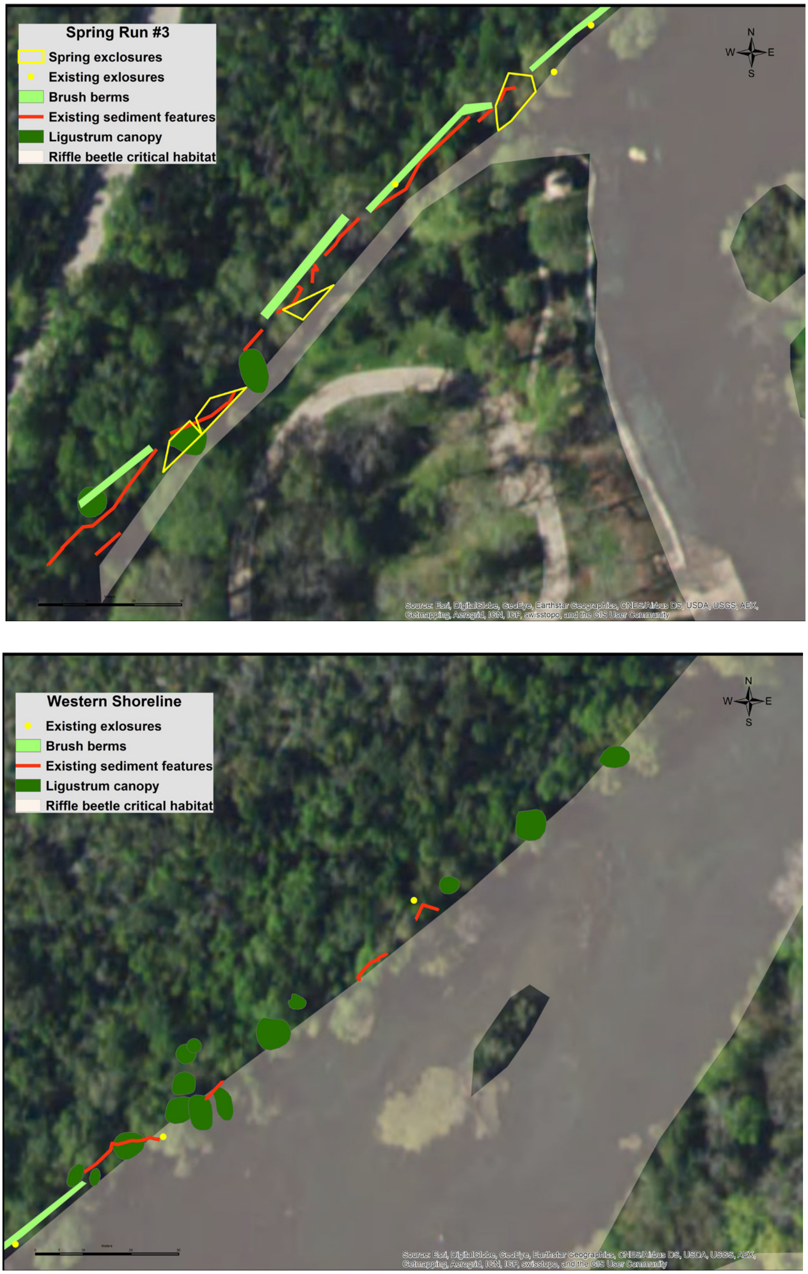



FIGURE 4-17 Locations of riparian management activities along Spring Run 3 (top) and the western shoreline of Landa Lake (bottom). SOURCE: Blanton and Associates (2018).

to reduce erosion and runoff near CSRB spring orifices. A total of 385 new native plants were planted within the project area. The riparian planting activities have had to contend with the reemergence of nonnative species that are competing with the newly replanted native species. Although riparian sediment and vegetation continued to be monitored, the 2017 HCP Annual Report (Blanton and Associates, 2018) has no discussion of the monitoring results.

### Riparian Restoration along the Old Channel

Riparian restoration along sections of the Comal River that are not habitat for the CSRB is done primarily for the purposes of improving fountain darter habitat via reduction of erosion and sedimentation that might inhibit the growth of SAV. In 2016, approximately 1,000 ft of previously eroding bank habitat along the Old Channel was replaced with stabilization structures to prevent continued erosion. This activity included using water-filled bladder dams to minimize sediment and debris entering the channel while recontouring the slope and installing toe-of-slope systems, mid-slope waler walls, run-on control berms, and drainage swales (Figure 4-18). At the end of the construction activities, erosion control matting was installed, and topsoil was applied and then hydroseeded with a native plant seed mix.

In 2017, similar nonnative removal and native replanting activities continued. Along certain parts of the channel, including adjacent to the golf course, fencing was erected and 10-ft buffers were delineated as no-mow zones to encourage the establishment of functional riparian zones. Monitoring and maintenance of these riparian areas were conducted, but the results of these activities are not discussed in the 2017 HCP Annual Report (Blanton and Associates, 2018). These activities are planned to continue downstream along the Comal River in 2018, with each new section first receiving treatment to remove invasive riparian plants and then subsequently having new native riparian plants planted. Similar to the remarks for evaluating riparian restoration success in habitats that directly impact the CSRB, there is a critical need to quantitatively evaluate native plant establishment success, bank erosion runoff, and aquatic sedimentation. The extent to which these riparian restoration activities will prevent sediment from entering aquatic habitats in both the short and long terms depends on how well the native species become established and function to reduce erosion.

### Riparian Improvements and Sediment Removal in the San Marcos System

Substantial riparian restoration has taken place within the San Marcos system, with similar nonnative removal and native planting occurring in

FIGURE 4-18 Riparian restoration along the Old Channel. SOURCE: Blanton and Associates (2017).

riparian zones along Ramon Lucio Park, Dog Beach Park, Rio Vista Park, Crooks Park, Bicentennial Park, City Park, and Sessom Creek Park. In San Marcos, the riparian replanting activities have been undertaken primarily to support recreation management by blocking access to the San Marcos River except at designated points (see the example in Figure 4-12). However, improving riparian coverage can also benefit the water quality of adjacent aquatic habitats by filtering runoff and reducing sedimentation from erosion. The goals of this work have been, among other things, to increase the width of the riparian zone to at least 15 meters, to maintain all treated and adjacent areas from Clear Springs to I-35 to address seed sources, and to remove invasive trees below I-35 (Furl, 2017).

Note that riparian restoration occurring in the vicinity of the San Marcos salamander (Spring Lake and the Spring Lake Dam region) is likely to be very important to the goal of maintaining silt-free gravel and hence to the habitat component of the biological objective for the salamander. Because riparian restoration is not a stated objective for any listed salamander, there is no discussion of this issue in the HCP annual reports. However, effective and sustained riparian restoration activities are likely to have positive effects on maintaining silt-free salamander habitat.

### Additional Considerations for Riparian Management Activities

There have been considerable changes over the last century to the riparian areas along both rivers (most notably the construction of numerous dams along the Comal River, beginning with the first flour mill in the 19th century). Apparently, large cypress (*Taxodium distichum*) trees once dominated wet locations along both rivers, with oak trees (*Quercus* spp.) on drier sites, intermingled with a diverse understory. There have already been some efforts to plant young cypress trees along the San Marcos River to restore what should eventually be a partially shaded canopy over large portions of the upper segments of the river. Hence, there are questions about how dense the canopy should be to match the needs of the listed fish and beetles on one hand and SAV species and bryophytes on the other hand. SAV and bryophytes prefer high light for highest productivity. However, if the overarching tree canopy is very open, water temperatures will rise, and if there are abundant nutrients in the water column, eutrophication would be expected, especially during low-flow periods. In contrast, if the stream bed is too deeply shaded by dense canopy, there will be low productivity of the SAV and bryophyte communities, which may limit fountain darter production (Best, 1984). More light measurements are needed in these reaches to determine if they are light limited or not. The success of reestablishing the native riparian plants themselves is also driven by light availability that presumably will not change unless the overstory trees are removed. In 2017, there was additional removal and pruning of some vegetation to increase light availability to the understory replanted native vegetation.

While there has been some effort to make visual and photographic assessments of how well the native riparian planting mediates soil erosion, there has been no quantitative measure of its success. For instance, while there is visual evidence of sediment accrual behind erosion control structures, there is no measurement of how the rate of this accrual occurs or if it will change once the native vegetation is established. Similarly, there is no measurement of how much sediment is being lost by these structures and entering the aquatic habitats, and there is no monitoring or measuring of aquatic sedimentation. Monitoring or measuring sedimentation and substrate impaction is necessary to evaluate the success of the riparian restoration activities relevant to the CSRB. Examples of how to monitor sedimentation of aquatic substrates can be found in Pasternack and Brush (1998), Knight and Pasternack (2000), and Pasternack et al. (2000). As part of the water quality monitoring program, there is turbidity monitoring in Spring Runs 1, 3, and 7. However, the turbidity loggers are not placed where they can monitor suspended sediment from riparian restoration, and turbidity is only being measured at one CSRB LTBG reach, Spring Run 3. A quantitative evaluation of the role that native riparian planting activities are having on erosion and aquatic sedimentation deposition is highly warranted.

Moreover, the long-term success of these M&M measures is dependent on the effectiveness of the erosion control structures. These structures are currently made from organic materials that naturally degrade, they are damaged by wildlife and park visitors, and they will require continued maintenance and replacement in forthcoming years. Similar issues arise with the drip irrigation system. A long-term (i.e., decades) plan for dedicating resources to the construction, expansion, maintenance, and replacement of the erosion control and other infrastructure would be useful.

There are studies that have evaluated the efficacy of riparian restoration efforts and found that removal of nonnative species and replanting with native species are complex activities that can be potentially negative by increasing areas of bare soil and compromising bank stability (see Beater et al., 2008). It has even been debated that nonnative species can have a conservation benefit (see Schlaepfer et al., 2011, and the rebuttal, Vitule et al., 2012).

### Will Riparian Restoration Achieve the Biological Objectives for CSRB?

While the removal of nonnative riparian plants and reestablishment of native species appears to be showing consistent success since the initiation of riparian restoration activities in 2013, the degree to which this activity is responsible for reducing sediment runoff and hence protecting CSRB habitat is not known. The installation of erosion control structures at the same time as planting, while rational to prevent immediate runoff, obfuscates assessing the success of native plant reestablishment in managing runoff. Monitoring of sediment accumulation in the structures showed that soil is being washed into and captured by the control structures, preventing runoff and deposition into Lake Landa. However, these same observations suggest that the bank habitat has not yet been stabilized by subsequent planting of native vegetation. There is no quantitative monitoring of aquatic sedimentation in the areas adjacent to riparian restoration. For these reasons, the Committee is **unable to determine** whether riparian management measures will achieve the biological objectives of the CSRB.

Despite this determination for riparian activities intended to improve CSRB habitat, a more definitive assessment can be made for the riparian restoration activities in areas where the CSRB is not routinely found (e.g., riparian restoration in the Old Channel of the Comal River and bank stabilization in the San Marcos system). The evidence presented in photographs makes it clear that the riparian restoration measures are effective for reducing erosion and sedimentation that might stymie the growth of SAV and for supporting recreation management by funneling people to permanent access points.

## NATIONAL FISH HATCHERY AND TECHNOLOGY CENTER REFUGIA

The HCP calls for establishment of both salvage and long-term refugia programs. These efforts apply to all covered species in both the Comal and San Marcos systems. The limited geographic distribution of these species leaves the populations vulnerable to extirpation throughout all or a significant part of their range.

The purpose of the salvage refugia program is to collect and maintain captive stocks of listed Edwards Aquifer species (and genes) so that individuals are available for reintroduction following a low-flow or other catastrophic event. The HCP requires the establishment of off-site refugia to maintain captive populations of the listed Edwards Aquifer species when it is determined that a significant loss is imminent due to a catastrophic event, such as prolonged drought, calling into question the likelihood of continued species existence in the wild. Specific triggers for salvage collections based on flow, habitat characteristics, or catch per unit effort of target organisms are specified in the HCP. (No salvage events were triggered in 2015 or 2017.)

The long-term refugia program is to house and protect adequate populations (and genes) of covered species; support appropriate research activities; develop protocols for husbandry, propagation, and effective reintroduction techniques; and expand knowledge of their biology, life histories, and genetic variation. For example, the CSRB is being housed and studied at the refugia both to inform improvements in the field monitoring of the beetle and to determine the best conditions for maintaining colonies over the long term.

Given delays in securing a contract for the long-term refugia due to legal questions, and the threat of drought conditions, refugia operations were initiated in a staggered, two-phase process. The first step consisted of establishing a Salvage Refugia Program aimed at quickly providing refuge capabilities to protect the covered species over the short term, ensuring against imminent salvage-trigger threats. This phase became operational in early 2016, and collections of covered species were initiated.

The second step consisted of establishing a Long-Term Refugia Program to provide a long-term facility and refugia for the covered species for the duration of the ITP. In 2016, the EAA Board of Directors approved a contract with the FWS for a Long-Term Refugia Operation, effective January 1, 2017. The contractor was to begin capturing seven different endangered species from their current habitat and bringing them to the FWS San Marcos Aquatic Resource Center located in San Marcos, Texas (the primary off-site refugia), and Uvalde National Fish Hatchery, located in Uvalde, Texas (the secondary off-site refugia).

During 2017, the FWS initiated hiring the necessary staff to perform refugia operations (husbandry, propagation, research), collect contractually required amounts of HCP covered species, and commence the design and construction of the EAA physical infrastructure used to house the HCP covered species. Construction is under way and expected to be completed in 2018. Primary long-term refugia populations are fully established for Texas wild rice, San Marcos salamanders, and fountain darters from the San Marcos River, and target numbers of fountain darters from the Comal River will likely be reached in 2018. Achieving target numbers for the other species will take at least several more years.

Details of the Salvage Refugia Research Plan are presented in the 2016 HCP Annual Report (Blanton and Associates, 2015, App. K2), along with summaries of the numbers of each species that have been collected and the research findings on the biology and life history of several of the covered species.

This M&M measure does not directly address any of the specific biological goals and objectives, but it serves as a potential safety net backing up all of them. The extent to which reintroduction would be successful is unknown and likely varies among species. Research conducted under this measure may inform ecological models for various covered species. Despite its inherent limitations, the Committee considers this M&M measure to be **effective**. To the extent possible, refugia populations should continue to be maintained in more than one location to reduce the risk of complete loss. Texas wild rice produces recalcitrant seeds that do not survive the desiccation necessary for conventional seed bank storage, but refugia personnel do maintain a bank of seeds on a rolling basis. Seeds are collected regularly and stored for six months, then used to grow new plants. Cryopreservation is a feasible alternative method of long-term propagule preservation for Texas wild rice (Walters et al., 2002). Currently, cryogenic storage is not being used for Texas wild rice propagules, but it could be considered. The refugia program serves as much more than an insurance policy for the listed species; applied research under this program is the primary means to discover more information about the life histories of these organisms that can inform future management and should be continued.

## CONCLUSIONS AND RECOMMENDATIONS

**The flow protection measures will be *effective* in meeting the flow component of the biological objectives for all listed species.** Throughout the 2014 drought during which both VISPO and Critical Period Management Stage IV and V restrictions were triggered, spring flows remained above threshold levels. Recent validation of the MODFLOW model during a drought period suggests that the model conservatively estimates both indicator-well levels and minimum spring flows, particularly at low flows. The model predicted that triggering of the four spring-flow protection measures would prevent simulated flows from going below the minimum HCP flow requirements during the Drought of Record. The rating for flow protection measures will move toward highly effective if results of the uncertainty analysis show that the errors are low or if model improvements continue to demonstrate that the model is biased low (i.e., conservatively underestimates well levels and spring flows).

**The water quality protection measures, focusing primarily on stormwater control, will be *somewhat effective* in meeting the water quality component of the biological objective for fountain darters in the Comal and San Marcos stream systems.** This assessment is based on whether the measures, many of which have yet to be implemented, are likely to keep water quality from further degrading or to improve water quality. The rating of somewhat effective is based on the difficulty in determining the effectiveness of SCMs as well as the uncertainty in how many projects will be implemented. Of the many suggestions given for how to improve the rating, the most important are tracking project implementation and functioning. There should be formalized project tracking to help with prioritization and success rates.

**The SAV restoration measures, including the replanting of Texas wild rice, will be *effective* in meeting the habitat component of the biological objective for Texas wild rice and fountain darters.** These measures have been in place since 2013 and have seen incremental and positive progress in moving the systems from being dominated by nonnative SAV, such as *Hydrilla* and *Hygrophila,* to housing a variety of native SAV species. Removal of nonnative SAV has reduced fountain darter habitat, but this was a known consequence and future plantings of native SAV combined with expanded areas should compensate. The planting program for Texas wild rice has been particularly successful. The ratings could move to highly effective if there were less reliance on intensive planting efforts and less dependence on bryophytes as fountain darter habitat in the Comal system.

**The recreational management measures will be *effective* in meeting the habitat component of the biological objectives for the San Marcos salamander and Texas wild rice.** Establishment of permanent river-access points is complete, including terraces and walls to stabilize the riverbank and facilitate river access by the public. Native vegetation has been planted between permanent access points to eliminate public access in these areas. Exclusion areas within the San Marcos River have been actively implemented and maintained when low-flow conditions occur, and substantial outreach efforts have been undertaken to ensure compliance by recreational users. Actions to improve the rating include enrollment of all outfitters in the COI program; better control of recreational access to the 50-meter stream reach immediately below the spillway; and sustaining, enforcing, and monitoring the suite of actions currently in place.

**The Committee is *unable to determine* whether riparian management measures will contribute to achieving the biological objectives of the CSRB.** This is due to a lack of quantitative monitoring of the riparian restoration efforts to show that they are preventing siltation of adjacent springs, as well as to the substantial maintenance requirements of erosion control structures. There is the potential for negative effects of nonnative plant removal and replanting activities, such as increased sedimentation of spring substrates. For the other riparian restoration activities (e.g., bank stabilization) in both systems that do not directly affect CSRB habitat, site visits and observations suggest that riparian restoration is effective for reducing erosion and sedimentation that might inhibit the growth of SAV and for supporting recreation management by funneling people to permanent access points.

**The refugia is *effective* in supporting the biological goals and objectives of the listed species.** Excellent progress has been made in establishing refugia populations of the listed species, and applied research conducted in conjunction with the program has already substantially increased the knowledge base for several of the species. Actions to support continued success include sustained maintenance of populations in more than one location, exploration of methods for long-term preservation of Texas wild rice propagules, and continued development of a vigorous applied research program.

## REFERENCES

Alan Plummer Associates, Inc. 2017. City of New Braunfels: Edwards Aquifer Habitat Conservation Plan Impervious Cover and Water Quality Protection—5.7.6 Water Quality Protection Plan, Phase I. Report. May 4.

Arthur, J. D., A. A. Dabous, and J. B. Cowart. 2005. Water-rock geochemical considerations for aquifer storage and recovery: Florida case studies. Pp. 327-339 in Underground Injection Science and Technology, Developments in Water Science, vol. 52, C.-F. Tsang and J. A. Apps (eds.). Amsterdam: Elsevier.

Arthur, J. D., A. A. Dabous, and C. C. Fischler. 2007. Aquifer storage and recovery in Florida: Geochemical assessment of potential storage zones. Pp. 185-197 in Management of Aquifer Recharge for Sustainability, P. Fox (ed.). Phoenix, AZ: Acacia.

Beater, M. M. T., R. D. Garner, and E. T. F. Witkowski. 2008. Impacts of clearing invasive alien plants from 1995 to 2005 on vegetation structure, invasion intensity and ground cover in a temperate to subtropical riparian ecosystem. South African Journal of Botany 74:495-507.

Beaty, W. V. 1975. Texas wildrice. Texas Horticultural Society 2:9-11.

Bell, C. D., , S. K. McMillan, S. M. Clinton, and A. J. Jefferson. 2016. Hydrologic response to stormwater control measures in urban watersheds. Journal of Hydrology 541:1488-1500.

Best, E. P. 1984. Models on metabolism of aquatic weeds and their application potential. Pp 254-273 in Aquatic Weeds: The Ecology and Management of Nuisance Aquatic Vegetation, A. H. Pieterse and K. J. Murphy (eds.). Oxford, UK: Oxford University Press.

BIO-WEST. 2016. Year One Report. Evaluation of the Life History of the Comal Springs Riffle Beetle from Egg to Adult: Phase I. EAHCP Project No. 147-15-HCP. December 21.

BIO-WEST and Watershed Systems Group, Inc. 2016. Submerged Aquatic Vegetation Analysis and Recommendations. Edwards Aquifer Habitat Conservation Plan. Contract No. 15-7-HCP.

Blanton and Associates. 2015. Edwards Aquifer Habitat Conservation Plan. 2014 Annual Report. http://eahcp.org/documents/EAHCP%202014%20Annual%20Report.pdf.

Blanton and Associates. 2016. Edwards Aquifer Habitat Conservation Plan. 2015 Annual Report. http://eahcp.org/documents/EAHCP%202015%20Annual%20Report%20Final.pdf.

Blanton and Associates. 2017. Edwards Aquifer Habitat Implementation Plan. 2016 Annual Report. http://eahcp.org/documents/EAHCPAnnualReport2016.pdf.

Blanton and Associates. 2018. Edwards Aquifer Habitat Conservation Plan. 2017 Annual Report. http://www.eahcp.org/files/admin-records/NEPA-and-HCP/EAHCPAnnualReport2017_(1).pdf.

Brown, R. A., and M. Borst. 2014. Evaluation of surface and subsurface processes in permeable pavement infiltration trenches. Journal of Hydrologic Engineering 20(2):04014041-12.

Davis, A. P. 2005. Green engineering principles promote low-impact development. Environmental Science & Technology 39:338A-344A.

EARIP (Edwards Aquifer Recovery Implementation Program). 2012. Edwards Aquifer Recovery Implementation Program Habitat Conservation Plan. http://www.eahcp.org/files/uploads/Final%20HCP%20November%202012.pdf.

Emerson, C. H., C. Welty, and R. G. Traver. 2005. Watershed-scale evaluation of a system of storm water detention basins. Journal of Hydrological Engineering 10(3):237-242.

Emery, W. H. P. 1967. The decline and threatened extinction of Texas wild rice (*Zizania texana* Hitchc.). Southwestern Naturalist 12(2):189-205.

Emery, W. H. P. 1977. Current status of Texas wild rice (*Zizania texana* Hitchc.). Southwestern Naturalist 22(3):389-406.

Filoso, S., S. M. Smith, M. R. Williams, and M. A. Palmer. 2015. The efficacy of constructed stream–wetland complexes at reducing the flux of suspended solids to Chesapeake Bay. Environmental Science & Technology 49(15):8986-8994.

Fletcher, T. D., H. Andrieu, and P. Hamel. 2013. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. Advances in Water Resources 51:261-279.

Furl, C. 2017. Conservation Measures → Biological Objectives → Biological Goals. Presentation to the National Academies' Committee to Review the Edwards Aquifer Habitat Conservation Plan. October 2.

Geosyntec Consultants and Wright Water Engineers, Inc. 2009. Urban stormwater BMP Performance Monitoring. Washington, DC: U.S. Environmental Protection Agency. http://www.bmpdatabase.org/Docs/ 2009%20Stormwater%20BMP%20Monitoring%20Manual.pdf.

Halff Associates, Inc. 2010. Initial Study on the Recreational Impacts to Protected Species and Habitats in the Comal and San Marcos Springs Ecosystems. November 3. http://earip.org/Reports/10-0930-Final-Report-b.pdf.

Hamel, P., E. Daly, and T. D. Fletcher. 2013. Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: A review. Journal of Hydrology 485:201-211.

Hamilton, M., and J. Boenig. 2017. Re-conceptualizing the Edwards Aquifer Authority Recharge Program: Staff Recommendations to Optimize and Protect the Edwards Aquifer. EAA Technical White Paper. 19 pp.

HDR Engineering, Inc. 2011. Evaluation of Water Management Programs and Alternatives for Springflow Protection of Endangered Species at Comal and San Marcos Springs. Report No. 12-01. Edwards Aquifer Authority

Hood, M. J., J. C. Clausen, and G. S. Warner. 2007. Comparison of stormwater lag times for low impact and traditional residential development. Journal of the American Water Resources Association 43(4):1036-1046.

John Gleason LLC. 2017. Water Quality Protection Plan for the City of San Marcos and Texas State University. Prepared for the City of San Marcos and Texas State University. January 1.

Knight, M. A., and G. B. Pasternack. 2000. Sources, input pathways, and distributions of Fe, Cu, and Zn in a Chesapeake Bay tidal freshwater marsh. Environmental Geology 39(12):1359-1371.

Leisenring, M., J. Clary, and P. Hobson. 2014. International Stormwater Best Management Practices (BMP) Database Pollutant Category Statistical Summary Report: Solids, Bacteria, Nutrients, and Metals. Geosyntec Consultants, Inc. and Wright Water Engineers, Inc.

Liu, A., N. Troshanov, J. Winterle, A. Zhang, and S. Eason. 2017. Updates to the MODFLOW Groundwater Model of the San Antonio Segment of the Edwards Aquifer. Edwards Aquifer Authority.

Livingston, E. H. 2000. Lessons learned about successfully using infiltration practices. Pp. 81-96 in National Conference on Tools for Urban Water Resource Management and Protection. EPA/625/R-00/001. Washington, DC: U.S. Environmental Protection Agency.

Loperfido, J. V., G. B. Noe, S. T. Jarnagin, and D. M. Hogan. 2014. Effects of distributed and centralized stormwater best management practices and land cover on urban stream hydrology at the catchment scale. Journal of Hydrology 519:2584-2595.

Lui, Y., V. F. Bralts, and B. A. Engel. 2015. Evaluating the effectiveness of management practices on hydrology and water quality at watershed scale with a rainfall-runoff model. Science of the Total Environment 511:298-308.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2017. Review of the Edwards Aquifer Habitat Conservation Plan: Report 2. Washington, DC: The National Academies Press.

NRC (National Research Council). 2009. Urban Stormwater Management in the United States. Washington, DC: The National Academies Press.

Pasternack, G. B., and G. S. Brush. 1998. Sedimentation cycles in a river-mouth tidal freshwater marsh. Estuaries 21(3):407-415.

Pasternack, G. B., W. B. Hilgartner, and G. S. Brush. 2000. Biogeomorphology of an upper Chesapeake Bay river-mouth tidal freshwater marsh. Wetlands 20(3):520-537.

Pence, N. 2018. Impervious Cover/Water Quality Protection, LID and Sediment Removal. Presentation to the National Academies Committee to review the Edwards Aquifer Habitat Conservation Plan. January 4.

Roy, A. H., S. J. Wenger, T. D. Fletcher, C. J. Walsh, A. R. Ladson, W. D. Shuster, H. W. Thurston, and R. R. Brown. 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: Lessons from Australia and the United States. Environmental Management 42:344-359.

Schlaepfer, M. A., D. F. Sax, and J. D. Olden. 2011. The potential conservation value of non-native species. *Conservation Biology* 25:428-437.

SWCA Environmental Consultants. 2014. Edwards Aquifer Habitat Conservation Plan, 2013 Annual Report. USFWS Permit No. TE63663A-0. http://eahcp.org/documents/FINAL_2013_EAHCP_Annual_Report.pdf.

STAC (Scientific and Technical Advisory Committee of the Chesapeake Bay Program). 2010. Small Watershed Monitoring Designs. STAC 10-004. http://www.chesapeake.org/pubs/232_D.E.Weller2010.pdf.

Strecker, E. W., M. M. Quigley, B. R. Urbonas, J. E. Jones, and J. K. Clary. 2001. Determining urban storm water BMP effectiveness. Journal of Water Resources Planning and Management 127:144-149.

Terrell, E. E., W. H. P. Emery, and H. E. Beaty. 1978. Observations on *Zizania texana* (Texas Wildrice), an Endangered Species. Bulletin of the Torrey Botanical Club 105(1):50-57.

Toran, L. 2016. Water level loggers as a low-cost tool for monitoring of stormwater control measures. Water 8(8):346.

Vitule, J. R. S., C. A. Friere, D. P. Vazquez, M. A. Nuñez, and D. Simberloff. 2012. Revisiting the potential conservation value of non-native species. Conservation Biology 26:1153-1155.

Vogel, J. R., T. L. Moore, R. R. Coffman, S. N. Rodie, S. L. Hutchinson, K. R. McDonough, A. J. McLemore, and J. T. McMaine. 2015. Critical review of technical questions facing low impact development and green infrastructure: A perspective from the Great Plains. Water Environment Research 87(9):849-862.

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. Morgan. 2005. The urban stream syndrome: Current knowledge and the search for a cure. Journal of the North American Benthological Society 24(3):705-723.

Walsh, C. J., D. B. Booth, M. J. Burns, T. D. Fletcher, R. L. Hale, L. N. Hoang, and A. Wallace. 2016. Principles for urban stormwater management to protect stream ecosystems. Freshwater Science 35(1):398-411.

Walters, C., D. H. Touchell, P. Power, J. Wesley-Smith, and M. F. Antolin. 2002. A cryopreservation protocol for embryos of the endangered species *Zizania texana*. Cryoletters 23:291-298.

Winterle, J. 2018. Updates to the MODFLOW Groundwater Model of the San Antonio Segment of the Edwards Aquifer. Presentation to the National Academies Committee to Review the Edwards Aquifer Habitat Conservation Plan. January 4.

# 5

# Overarching Issues

The preceding chapters focus on assessing whether the biological objectives in the Habitat Conservation Plan (HCP) will meet the biological goals and on the effectiveness of minimization and mitigation (M&M) measures to meet the biological objectives. In reality, both the biological goals and objectives are imperfect targets that were defined many years ago during the development of the HCP—that is, without the benefit of the more recent information that has been collected on the system. In addition, there are potential stressors to the system that may be more severe than the Drought of Record on which the HCP was based. Finally, it must be recognized that the ultimate success of the HCP is based upon the protection of the listed species and not the surrogates for that protection, which are the biological goals. As the Edwards Aquifer Authority (EAA) plans for implementation of Phase 2 of the HCP and ultimately a renewal of the incidental take permit, it should begin to consider several overarching issues and concerns that may ultimately suggest improvements to the biological goals and objectives to better protect the listed species.

## FOUNTAIN DARTER

Although the habitat-based biological goals for the fountain darter are reasonable because they are easy to measure and quantify (see Chapter 2), the ultimate goal is to ensure that the fountain darter population is sufficiently large to provide a buffer against environmental variation and other possible factors that can affect population abundances. This requires estimates of the total numbers of fountain darters in each system. Various reports present fountain darter abundances obtained by multiplying fountain darter densities times the acreage of submerged aquatic vegetation (SAV), and then summing these products over the long-term biological goal (LTBG) and restoration reaches. The Committee is not aware of analyses that support the idea that the target numbers of fountain darters in the LTBG and restoration reaches calculated by this method would reduce the risk of jeopardy or how much this calculated abundance would contribute to recovery. Various estimates of fountain darter population abundance are available from field data (Schenck and Whiteside, 1976; Linam et al., 1993) and used with fountain darter population modeling (Grant et al., 2017). Further exploration of the population abundance of fountain darters, especially with the monitoring data available and commonly used modeling tools, could help determine the viable population abundance.

An approach to examining how well population abundances offer a buffer to variation and can lead to recovery of the species is population viability analysis (PVA) modeling. Modeling analyses to determine viable population estimates and project recovery trajectories in response to restoration are commonly used for well-studied species in biological opinions and are often part of the broader conservation strategy, of which the HCP is part. PVA methods are well documented and relatively easy to apply (Brook et al., 2000; Beissinger and McCullough, 2002; Possingham et al., 1993). The analyses done to date, including the fountain darter ecological modeling (Grant et al., 2017), are considered deterministic approaches that do not explicitly deal with possible underachievement of goals (contingency planning) or stochastic events. In contrast, PVA can directly address the question, How many fountain darter adults are needed for a viable population that is resistant to take, drought, and massive loss of habitat? It would be nice to know that as the EAA fine-tunes the biological goals (as was done recently via the nonroutine adaptive management action), there is some confirmation of the total numbers of fountain darters that are dictated by the current habitat-based goals. The information needed to develop a PVA model for fountain darters is available. Such an effort could use the same approach of teaming local experts with population ecologists as used with the fountain darter ecological model.

For the fountain darter in each system, a challenge for PVA modeling is deriving how flow and habitat influence stage duration (growth), mortality, and reproduction. These three vital rates determine the population growth rate in models commonly used for PVA analyses. Much has been learned about fountain darters through the Applied Research Program, continued monitoring, and responses to extreme events and restoration, and much of the needed information is now available as part of the development of the existing fountain darter ecological model. Whether the information is sufficient to develop the relationships is worth exploring. However, one can make significant progress by determining how expected habitat and flows would affect these process rates without actually requiring explicit functions in the model; a range of changes in growth, mortality, and reproduction expected from habitat and flow conditions would be considered (see the "implicit approach" in Rose et al., 2015).

The results of a PVA would complement the habitat-based goals of the HCP by providing information on the effectiveness of the habitat-based goals in achieving healthy and sustainable fountain darter populations. Such analyses would allow for determination of which life stages and processes (growth, mortality, reproduction) provide the largest boost to the population, as well as the largest risks of decline. These results can be used to influence the specifics of how habitat and flow objectives can be formulated to be more effective ecologically and more efficient economically.

PVAs for organisms other than fountain darters could be similarly useful in better understanding the success of the species and in identifying data gaps. There are PVA models that can be used for data-limited situations (typical of most of the listed species in the Edwards Aquifer) (see Beissinger and McCullough, 2002) and plant species (Zeigler et al., 2013). Note, however, that PVA is not a common approach to evaluating management of SAV populations because all aquatic plants are clonal in nature, such that recruitment cannot be simply characterized in terms of sexual reproduction. This is not to say that PVA could not be useful in this context, but there is much additional data collection that would be required, such as documentation of seed banks and dispersal and characterization of the role of clonal reproduction versus ramets from seeds. These aspects of recruitment and dispersal were difficult to capture in the SAV modeling that was attempted for these systems because of the lack of data.

## SUBMERGED AQUATIC VEGETATION

While the existing M&M measures for SAV were found to be effective (see Chapter 4), there are some issues worth considering as work proceeds and certainly in planning for the next phase of the HCP. The Committee suggests a relaxation of the targets for species-specific areal SAV coverages and a stronger attempt to identify which factors control SAV success. Both of these suggestions might lead to lower overall effort without sacrificing the ultimate goal for fountain darters.

The first issue is the continual maintenance required to reach or hold ground on the specific SAV coverage targets—targets that have been adaptively modified already with clear and substantiated justification. There are two main lines of argument suggesting specific areal targets may not be necessary. First, and most directly relevant to the fountain darter, is the relatively small difference in fountain darter densities across the species of

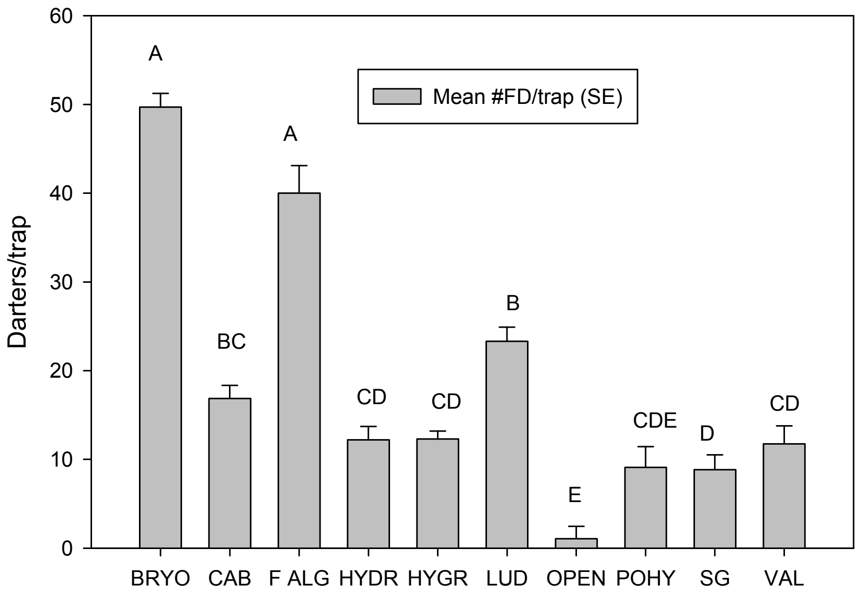



FIGURE 5-1 Mean number of fountain darters found in each type of submerged aquatic vegetation sampled with drop nets. Values shown are all data (both systems, all reaches combined) for vegetation types with at least 47 drop-net samples. Letters above the bars show which types are different from each other (Tukey's HSD). BRYO = bryophyte; CAB = *Cabomba*; F ALG = filamentous algae; HYDR = *Hydrilla*; HYGR = *Hygrophila*; LUD = *Ludwigia*; OPEN = no vegetation; POHY = *Potamogeton/Hygrophila*; SG = *Sagittaria;* VAL = *Vallisneria*. SOURCE: Committee manipulation of Edwards Aquifer Authority data.

SAV subject to active management (Figure 5-1). This is also apparent in the statistical analysis described in Appendix K3 of the 2017 HCP Annual Report (Blanton and Associates, 2018). The big differences are between bryophytes, filamentous algae, and the rest of the SAV species. In particular, the species most commonly managed (*Ludwigia*, *Sagittaria*, *Cabomba*, and *Potamogeton*) are not substantially different from one another, with high variability about the mean. This brings into question the fine-scale, precise management of areal targets that is currently being implemented; indeed, there is even mention (in Appendix L of 2017 HCP Annual Report—Blanton and Associates, 2018) of removal of *Ludwigia* and *Cabomba* if the target area is exceeded. Such strict interpretation of the species-specific areal targets may come at the expense of fountain darter habitat maintenance, generally. It might be worth running some modeling scenarios to see what kind of changes in relative SAV cover are necessary to shift estimated fountain darter abundances. However, continual monitoring will remain necessary because either directional changes in coverage or establishment of new invasive species may lead to undesirable conditions.

The second line of argument to rethinking the SAV targets is to better understand controls on SAV in general and relative species contributions in particular. For example, there are likely only so many potential acres of *Ludwigia* habitat, and the target for *Ludwigia* should reflect that potential, but one cannot compute that potential without more information on what the drivers are for *Ludwigia*. There are many environmental factors and biotic interactions affecting SAV, and at present it is not clear that their relative importance has been worked out. The SAV submodel of the fountain darter ecological model (Grant et al., 2017) represents one effort to synthesize mechanistic understanding of how these factors affect SAV. However, as the Committee previously outlined, there are significant omissions and drawbacks to that modeling effort (NASEM, 2016). For instance, there is repeated mention of light limitation, but this shallow, clear-water system seems unlikely to be light limited in the usual sense. The SAV ecological submodel lays out environmental parameters (PAR, extinction by the water column) showing that about 75 percent of incident light would reach 2-m depth, which even on a not very sunny day (1,000 uE per $m^2$/s) yields light ~ 20 times the half-saturation value used in the model (14 uE per $m^2$/s). The model does include a significant plant-shading effect such that competition for light may significantly shift species growth rates, but this is a normal "sorting" of species rather than some environmental control on initial establishment. Given the fairly small differences in fountain darter abundance across the vegetation types under active management, some shifting in SAV species coverage due to competition for light seems unlikely to greatly harm the fountain darter population.

Flow velocity is another factor often implicated in SAV species habitat selection. Across a reasonable range of modeled discharge conditions there was no evidence of response of SAV cover to variation in discharge (Appendix K4, HCP Annual Report 2017—Blanton and Associates, 2018), but this is likely due to the omission of flow dependency in the model formulations (NASEM, 2016). On the other hand, the SAV report (BIO-WEST and Watershed Systems Group, 2016) suggests that planting success at least partially depends on flow conditions, and so the potential influence of flow seems worthy of further investigation. Nutrient limitation is dismissed as a potential control, even though these are low-phosphorus systems. There is likely to be substantial local knowledge or experience gained by the contractors about what environmental factors control which species of SAV. Should new efforts to improve mechanistic understanding proceed, an opportunity may exist to evaluate SAV species targets with the benefit of species-specific habitat requirements that would better inform restoration efforts.

Overall, given the effort and cost of maintaining specific coverage targets for SAV, it seems justified to consider a lower level of management with the exception of monitoring for invasive species. If a slightly different blend of coverages leads to an indistinguishable darter population size, then some relaxation seems warranted. In addition, better understanding of controlling factors would lend more confidence and effectiveness to SAV management.

## MACROINVERTEBRATE DATA ANALYSIS

Although the macroinvertebrate monitoring program is not formally part of the HCP, a long-term monitoring program has been in place since 2003 (Beaver Creek Hydrology, 2018; Perkin, 2018; Perkin et al., 2018). The Committee applauds the EAA for the addition, continuation, and refinement of the macroinvertebrate monitoring program, as it responds to a recommendation for developing a more holistic ecological understanding of the two ecosystems (NRC, 2015). Multiple aspects of the macroinvertebrate monitoring program provide great potential to the HCP, and the Committee urges the EAA to continue to tap into that potential. First, macroinvertebrate monitoring could serve as a general proxy for the overall ecosystem health of the two spring systems, like that routinely done throughout the United States for wadeable streams (e.g., Barbour et al., 1999; Bonada et al., 2006). Second, the general monitoring of aquatic invertebrates can provide substantial understanding of, and a powerful database on, the complex natural history of the aquifer. Third, comparisons of the general invertebrate community composition and dynamics could be paired statistically with Comal Springs riffle beetle (CSRB) population estimates to provide an evaluation of the cotton-lure sampling approach. Finally, standard ecological community analyses for macroinvertebrates could ultimately serve as a useful surrogate metric for evaluating the overall HCP, and specifically, the efficacy of the M&M measures related to protecting all troglobitic invertebrates in the Edwards Aquifer.

While the macroinvertebrate monitoring program is a positive development, there remain limitations to the current program and analyses. It would seem that given the importance of water quality as exemplified by the biological goal of no more than 10 percent variance from historical conditions, water quality evaluation of associated reaches should accompany macroinvertebrate sampling. Not only would such data be useful in exploring relationships between community composition and structure and water quality, the data could be used to provide quantitative support for the assumption that ≤10 percent deviation in water quality provides sufficient protection to the covered invertebrates and other troglobitic species. The latter issue may be addressed with the new Texas Commission on Environmental Quality (TCEQ)-based sampling protocol (2014; adopted in 2017), but might also be addressed with the collections associated with the refugia program, since collections were made relatively frequently throughout 2017. Ultimately, a solid temporal and spatial monitoring program, including water quantity and quality measures, will be required. Whether through the refugia collections or via independent monitoring, such a program would prove invaluable in providing a solid link between the LTBGs and the macroinvertebrate communities, including the covered species.

To maximize the utility of the macroinvertebrate monitoring, it also will be important to simultaneously maintain the old and new sampling regimes to provide enough overlap so that the two datasets can be compared for complementarity, and ultimately be combined potentially for a longer-term analysis of population and community dynamics. There will be limitations to combining the two datasets, but the exercise could prove valuable and render the older data useful in assessing the efficacy of the HCP. Finally, we encourage the EAA to bring both the data generated through Applied Research projects and the data being collected under the auspices of the refugia program to bear on better comprehension of the interrelationships between invertebrate population estimates and water quality and other biological variables in the two systems.

## INVASIVE SPECIES, EXOTICS, AND DISEASE

The species covered by the HCP are adapted to a stable physical environment and a biotic community with which they have co-evolved. The HCP articulates a broad array of detailed measures to protect covered species (e.g., adequate spring flows and water quality, native vegetation restoration, recreation management), largely by maintaining this stability. While most of the threats that these measures address are generally straightforward to identify, some, such as those posed by potential introductions of nonnative species or diseases, are more nebulous.

Both the Recovery Plan (FWS, 1996) and the HCP note that nonnative species can pose a significant threat to the listed species via competition, habitat modification, or predation, or as vectors for diseases or parasites. Decreased spring flows may exacerbate the problems posed by nonnative species. Thus, the HCP addresses control of nonnative species "to minimize and mitigate the impacts of low flows."

Current control efforts focused on nonnative species are already present in the Comal and San Marcos systems (Blanton and Associates, 2018). In addition to extensive efforts to remove nonnative vegetation, both the City of New Braunfels and the City of San Marcos devote substantial effort to monitoring and removal of nonnative fishes—primarily suckermouth catfish (*Hypostomus plecostomus*), sailfin catfish (*Pterygoplichthys disjunctivus*), and blue tilapia (*Oreochromis aureus*)—via spearfishing, bow fishing, gill netting, seining, and other means. Effort is also devoted to monitoring and removal of giant ramshorn snail (*Marisa cornuarietis*), a nonnative herbivore, and the red-rimmed melania (*Melanoides tuberculatus*), a non-native snail that is the first intermediate host of *Centrocestus formosanus*, the gill parasite that infects fountain darters. There are, however, instances where management of existing, established invasive species may have short-term negative or inconclusive effects on attainment of goals. For instance, large areas of invasive SAV species have been removed from the two systems despite knowledge that these species were habitat for fountain darter (NASEM, 2017). Additionally, removal of exotics from riparian areas may have left exposed soil susceptible to erosion. These examples suggest that management of existing invasive species requires individual consideration rather than blanket actions.

Unidentified future invaders may pose even greater risks than those already present in these systems. The literature is replete with accounts of well-meaning, intentional introductions of nonnative species having serious, and sometimes catastrophic, unanticipated consequences. Such impacts may be even more likely for unintentional introductions. While some species known to prey on fish or other aquatic organisms might be immediately recognized as a potential threat to fountain darters, salamanders, or invertebrates, it would be unwise to consider even apparently benign species as safe. For example, red shiners (*Cyprinella lutrensis*) have been introduced into many streams in the western United States and often occur at high densities. Although not typically thought of as a piscivore, this small cyprinid will feed on larval fishes, and its predation has been implicated as a major constraint on recruitment of the Colorado pikeminnow (*Ptychocheilus lucius*), an endangered species endemic to the Colorado River basin (Bestgen et al., 2006).

Species introductions can also introduce diseases or parasites. Although background levels of pathogens are common components of natural ecosystems, some outbreaks, particularly of introduced pathogens (e.g., fish diseases such as largemouth bass virus, whirling disease) can cause major mortality and alterations to community composition. A fungal rust species, *Ustilago esculenta*, is endemic to *Zizania latifolia*, a congener of Texas wild rice native to China, and known to infect other plant species where it is introduced. Watson (1991) reported a significant outbreak of *Ustilago esculenta* on wild rice crops in California. The disease attacks plants at flowering, and it is easily spread on seeds by wind (Terrell, 2007). Inadvertent introduction of this fungal species to the San Marcos system could be catastrophic for Texas wild rice. The slime mold *Labyrinthula* *zosterae* infected populations of the SAV *Zostera marina* as "wasting disease" and led to regional declines in this species in the 1930s (Muehlstein et al., 1991). *Labyrinthula* spreads via rhizomes and root structures, making clonal plants particularly susceptible. This vulnerability may extend to other SAV species and fungal infections. The chytrid fungus, *Batrachochytrium salamandrivorans*, a deadly pathogen that can precipitate severe declines and extinctions of salamander species, has emerged as a major conservation concern in Europe. Though it has not yet been detected in the United States, it would pose a severe threat to San Marcos salamanders and Texas blind salamanders if it were to reach the Edwards Aquifer system. Other environmental stressors (e.g., low flows and declines in water quality) can make organisms more vulnerable to disease.

The HCP is heavily focused on maintaining homeostasis of the unique environments inhabited by the covered species. Refugia populations provide redundancy and genetic representation to reestablish populations in the wild once habitat has been restored after a catastrophic event. But some events, such as introduction and establishment of a high-impact nonnative species, could make these systems permanently uninhabitable for one or more covered species, even if all these suitable habitat conditions are maintained. The opportunity to eradicate an introduced species is often limited to a short period before it becomes abundant or widely distributed. Once a population is well established, it can be difficult or impossible to eliminate, rendering reintroduction of covered species from refugia populations infeasible or ineffective.

It is understandable that HCP efforts have been largely focused on dealing with threats that are clear and present rather than potential threats that may or may not be realized in the future. Nonetheless, the threat posed by potential introduction of a nonnative species needs additional attention, since such an event may pose the greatest risk to long-term viability of covered species in the wild. There is an urgent need to develop and implement a plan for early detection of nonnative species and for rapid response to eradicate them before they become established. Given the intensive sampling and monitoring that occur in both spring systems, formalizing an early detection strategy should not be difficult. The plan for responding to a new invader will need to have contingencies for different types of species. Risk analysis is an established approach for responding to existing or potential invasive events and has formed the basis for many management and policy decisions (e.g., Lodge et al., 2016).

Given that humans are the likely vector for nearly all species introductions (and that species introductions can be vectors for disease and parasite introductions), efforts to educate the public about the potential catastrophic effects of species introductions are critical. Both the City of New Braunfels and the City of San Marcos conduct multipronged educational campaigns


FIGURE 5-2 Fish drop-off pond at the Discovery Center. SOURCE: Blanton and Associates (2018).

designed to inform the public about the negative impacts of introducing nonnative aquarium and bait species. These efforts include distribution of educational materials on social media websites and via fliers posted in Texas State University dormitories and local pet stores (though not all are willing to participate), outreach at public events, signage at river access points, presentations to school groups and local organizations, and establishment of a pet fish drop-off location in San Marcos to deter aquarium dumps into the river system (Figure 5-2). The City of New Braunfels has established an ordinance prohibiting fishing with live bait, and the City of San Marcos has also prohibited release of fish, plants, or other organisms into waters in its city parks. These efforts are important and should be expanded to frequently and consistently reach all members of the greater community. Given the potentially irreversible nature of most introductions, multiple layers of deterrence are warranted.

## CATASTROPHIC EVENTS

The HCP represents a detailed and comprehensive planning process that is focused on meeting the recognized challenges to the listed species and the Comal and San Marcos spring and river systems. Increasingly, however, there is the potential for catastrophic events that are far outside the historical record and could pose unrecognized challenges to listed species and the systems. Although not part of the HCP, these should begin to receive evaluation for possible inclusion in future take permits and HCP planning.

The type of events that might affect the function of the system is illustrated by the behavior of Hurricane Harvey. On August 25, 2017, Hurricane Harvey came ashore between Houston and Corpus Christi and stalled, ultimately turning toward the north and settling over east Texas. More than 40 inches of rain fell in areas around Houston and Beaumont and caused catastrophic flooding and substantial erosion in waterbodies such as the San Jacinto River. What if Harvey had stalled closer to San Antonio and over the Comal and San Marcos rivers? What if climate change increased the frequency and intensity of such events in central Texas? Loss of habitat in these systems due to storm-related erosion was noted in a storm event during October 2015 (Blanton and Associates, 2016). The stormwater control measures being put in place (Chapter 4) would likely reduce the impacts of smaller storms but would be completely overwhelmed by an event such as Hurricane Harvey. Although the volume of water available to fall as rain would likely be reduced because of the area's inland location, such an event could completely destroy much of the restored SAV in the Comal and San Marcos rivers, directly affecting Texas wild rice and fountain darter habitat. Hutchinson and Foote (2017) show no effects on SAV coverage for either system across a range of discharge up to 450 cfs, although they suggest that minor losses would be experienced at 1,000 cfs, and flows of 4,000 cfs could scour much of the SAV. The October 2015 event exhibited far higher instantaneous flows: 20,900 cfs in the San Marcos and 14,100 cfs in the Comal (Blanton and Associates, 2016), suggesting that the river systems and SAV may be more resilient than Hutchinson and Foote (2017) suggest. A high-rainfall event could also lead to substantial erosion and sedimentation in areas of the rivers, affecting silt-sensitive species. Particularly significant would be riparian bank failure along the western edge of Landa Lake, which could lead to siltation of the spring runs housing the CSRB.

It may not be possible to completely plan for such an event, but evaluating the potential impacts may be useful. Organisms with a substantial portion of their life cycle in the aquifer, such as the Texas blind salamander, may be largely unaffected, whereas fountain darter, SAV, and Texas wild rice populations may be severely affected. The refugia may be the best and perhaps only means of restoring the populations of these species once the habitat has been restored, although an event that decimates both the river systems and the primary refugia located in the same area cannot be eliminated from consideration.

The MODFLOW model is a potential tool to partially address some scenarios that could occur in the future. Results of the model parameter estimation and uncertainty analysis may inform refinement or bracketing parameters in future scenarios. For example, climate variations may lead to observations that such events are more frequent, last longer, and exhibit greater intensity than is found in the historical record. As mentioned in Chapter 4, asymmetrical droughts across the model domain and variations in recharge and interformational flow could lead to precipitous declines in spring flow. These scenarios could impact whether the triggers for flow protection measures predict the timing of declines. The MODFLOW model could inform adaptive management specifically by evaluating how the four flow protection measures operate in extreme scenarios such as these. Other modeling tools would be needed to evaluate other processes, for example, the effect of extreme events on overland flow, surface water hydrology, sediment transport, and habitat loss.

This discussion of future scenarios is not to suggest that EAA should undertake formal contingency planning or expenditures to build resilience in the face of events such as these (at least without a better understanding of the potential likelihood of their occurrence). However, an examination of how the system might respond to such events may make them easier to address should such events occur.

## FINAL THOUGHTS

In keeping with its statement of task, the Committee has largely focused on the biological goals and objectives as identified in the current HCP. Some of the challenges identified in this chapter, however, go beyond the scope of the HCP and may ultimately limit the ability of the HCP to protect the listed species. In the future, as the HCP is revised and renegotiated, the Committee hopes that the new information being collected will allow a more holistic look at the spring and river systems in order to address challenges that the current HCP could not. Each iteration of the HCP offers an opportunity for improvements and to apply lessons learned. Sources of new information include the results of the Applied Research Program, the routine monitoring data and those data collected to support and evaluate the M&M measures, as well as the recommendations of the three previous National Academies reports (NRC, 2015; NASEM, 2016, 2017). It is typical in this type of review process involving several years, three committees, and four reports for recommendations to get lost and for some that the EAA thought they addressed (see implementation reports – EAA, 2015, 2017) to warrant revisiting. As part of the review process for this report, the Committee recommends that the EAA do an end-of-the-review synthesis and review all of the recommendations again. Over time, results and recommendations that may not appear useful or relevant may become so as knowledge is gained about the system.

## REFERENCES


Barbour, M. T., J. Gerritsen, B. D. Snyder, and J. B. Stribling. 1999. Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates, and Fish. EPA 841-B-99-002. Washington, DC: U.S. Environmental Protection Agency, Office of Water.

Beaver Creek Hydrology. 2018. Statistical Analysis of the San Marcos and Comal Springs Aquatic Ecosystems Biomonitoring Datasets. Edwards Aquifer Authority. http://www.eahcp.org/files/admin-records/NEPA-and-HCP/Beaver_Creek_Statistical_Analysis_of_BioMonitoring_datasets.pdf.

Beissinger, S. R., and D. R. McCullough. 2002. Population Viability Analysis. Chicago: University of Chicago Press.

Bestgen, K. R., D. W. Beyers, J. A. Rice, and G. B. Haines. 2006. Factors affecting recruitment of young Colorado pikeminnow: Synthesis of predation experiments, field studies and individual-based modeling. Transactions of the American Fisheries Society 135:1722-1742.

BIO-WEST and Watershed Systems Group, Inc. 2016. Submerged Aquatic Vegetation Analysis and Recommendations. Edwards Aquifer Habitat Conservation Plan. Contract No. 15-7-HCP. June.

Blanton and Associates. 2016. Edwards Aquifer Habitat Conservation Plan. 2015 Annual Report. http://eahcp.org/documents/EAHCP%202015%20Annual%20Report%20Final.pdf.

Blanton and Associates. 2018. Edwards Aquifer Habitat Conservation Plan. 2017 Annual Report. http://www.eahcp.org/files/admin-records/NEPA-and-HCP/EAHCPAnnualReport2017_(1).pdf.

Bonada, N., N. Prat, V. H. Resh, and B. Statzner. 2006. Developments in aquatic insect biomonitoring: A comparative analysis of recent approaches. Annual Review of Entomology 51:495-523.

Brook, B. W., J. J. O'Grady, A. P. Chapman, M. A. Burgman, H. R. Akçakaya, and R. Frankham. 2000. Predictive accuracy of population viability analysis in conservation biology. Nature 404(6776):385-387.

EAA (Edwards Aquifer Authority). 2015. National Academy of Sciences Review of the Edwards Aquifer Habitat Conservation Plan: Report 1 Implementation Plan. August 20.

EAA. 2017. Edwards Aquifer Habitat Conservation Plan: Report 2 Implementation Plan. July 31.http://www.eahcp.org/files/uploads/Final_Report_2_Implementation_Plan_2017_07_31.pdf.

FWS (U.S. Fish and Wildlife Service). 1996. San Marcos and Comal Springs and Associated Aquatic Ecosystems (Revised) Recovery Plan. Albuquerque, NM: FWS. http://www.eahcp.org/documents/1996_FWS_SanMarcosComalRevisedPlan.pdf.

Grant, W., T. Swannack, R. Wang, T. Hardy, G. Ward, R. Doyle, T. Bonner, and BIO-WEST, Inc. 2017. Fountain Darter Modeling System for the Comal and San Marcos Rivers. May 19.

Hutchinson, J. T., and J. Foote. 2017. Distributional Patterns of Aquatic Macrophytes in the San Marcos and Comal Rivers from 2000 to 2015. Final Report Edwards Aquifer Authority Proposal No. 156-16-HCP. The University of Texas at San Antonio.

Linam, G. W., K. B. Mayes, and K. S. Saunders. 1993. Habitat utilization and population-size estimate of fountain darters, *Etheostoma fonticola,* in the Comal River, Texas. Texas Journal of Science 45(4):341-348.

Lodge, D. M., P. W. Simonin, S. W. Burgiel, R. P. Keller, J. M. Bossenbroek, C. L. Jerde, A. M. Kramer, E. S. Rutherford, M. A. Barnes, M. E. Wittmann, W. L. Chadderton, J. L. Apriesnig, D. Beletsky, R. M. Cooke, J. M. Drake, S. P. Egan, D. C. Finnoff, C. A. Gantz, E. K. Grey, M. H. Hoff, J. G. Howeth, R. A. Jensen, E. R. Larson, N. E. Mandrak, D. M. Mason, F. A. Martinez, T. J. Newcomb, J. D. Rothlisberger, A. J. Tucker, T. W. Warziniack, and H. Zhang. 2016. Risk analysis and bioeconomics of invasive species to inform policy and management. Annual Review of Environment and Resources 41:453-488.

Muehlstein, L. K., D. Porter, and F. T. Short. 1991. *Labyrinthula zosterae* sp. nov., the causative agent of wasting disease of eelgrass, *Zostera marina*. Mycologia 83(2):180-191.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2016. Evaluation of the Predictive Ecological Model for the Edwards Aquifer Habitat Conservation Plan: An Interim Report as Part of Phase 2. Washington, DC: The National Academies Press.

NASEM. 2017. Review of the Edwards Aquifer Habitat Conservation Plan: Report 2. Washington, DC: The National Academies Press.

NRC (National Research Council). 2015. Review of the Edwards Aquifer Habitat Conservation Plan: Report 1. Washington, DC: The National Academies Press.

Perkin, J. 2018. Preliminary Evaluation of Long-Term EAHCP Biomonitoring Data. Presentation to the National Academies Committee to Review the Edwards Aquifer Habitat Conservation Plan. January 4.

Perkin, J. S., E. Kosnicki, and J. Jackson. 2018. Analysis of the Comal Springs and San Marcos Springs Long-Term Monitoring Dataset. Edwards Aquifer Authority.

Possingham, H. P., D. B. Lindenmayer, and T. W. Norton. 1993. A framework for the improved Possingham, H. P., D. B. Lindenmayer, and T. W. Norton. 1993. A framework for the improved management of threatened species based on population viability analysis (PVA). Pacific Conservation Biology 1(1):39-45.

Rose, K. A., S. Sable, D. L. DeAngelis, S. Yurek, J. C. Trexler, W. Graf, and D. J. Reed. 2015. Proposed best modeling practices for assessing the effects of ecosystem restoration on fish. Ecological Modelling 300:12-29.

Schenck, J. R., and B. G. Whiteside. 1976. Distribution, habitat preference and population size estimate of *Etheostoma fonticola*. Copeia (4):697-703.

TCEQ (Texas Commission on Environmental Quality). 2014. Surface Water Quality Monitoring Procedures, Volume 2: Methods for Collection and Analyzing Biological Assemblage and Habitat Data. RG-416. Water Quality and Planning Division, TCEQ.

Terrell, E. E. 2007. *Zizania* L. Pp. 47-51 in Flora of North America, vol. 24, M. E. Barkworth, K. M. Capels, S. Long, L. K. Anderton, and M. B. Piep (eds.). New York: Oxford University Press.

Watson, T. 1991. Smut of Manchurian wild rice caused by *Ustilago esculenta* in California. Plant Disease 75(10):1075D.

Zeigler, S. L., J. P. Che-Castaldo, and M. C. Neel. 2013. Actual and potential use of population viability analyses in recovery of plant species listed under the U.S. Endangered Species Act. Conservation Biology 27:1265-1278.

# Acronyms

| | |
|---|---|
| ASR | aquifer storage and recovery |
| BMP | best management practice |
| cfs | cubic feet per second |
| COI | Certificate of Inclusion |
| CSRB | Comal Springs riffle beetle |
| DO | dissolved oxygen |
| EAA | Edwards Aquifer Authority |
| EAHCP | Edwards Aquifer Habitat Conservation Plan |
| EARIP | Edwards Aquifer Recovery Implementation Program |
| ESA | Endangered Species Act |
| FWS | U.S. Fish and Wildlife Service |
| HCP | Habitat Conservation Plan |
| HSI | habitat suitability index |
| ITP | incidental take permit |
| LTBG | long-term biological goal |

| | |
|---|---|
| M&M | minimization and mitigation |
| | |
| NASEM | National Academies of Sciences, Engineering, and Medicine |
| NRC | National Research Council |
| | |
| PVA | population viability analysis |
| | |
| RWCP | Regional Water Conservation Program |
| | |
| SAV | submerged aquatic vegetation |
| SAWS | San Antonio Water System |
| SCM | stormwater control measure |
| SMS | San Marcos salamander |
| SOP | standard operating procedure |
| SSA | State Scientific Area |
| | |
| TCEQ | Texas Commission on Environmental Quality |
| TPWD | Texas Parks and Wildlife Department |
| TWR | Texas wild rice |
| | |
| USGS | U.S. Geological Survey |
| | |
| VISPO | Voluntary Irrigation Suspension Program Option |
| | |
| WQPP | Water Quality Protection Plan |
| WSTB | Water Science and Technology Board |

# Appendix

# Biographical Sketches of Committee Members and Staff

**Danny D. Reible** (NAE) is currently the Donovan Maddox Distinguished Engineering Chair at Texas Tech University. He previously served as director of the multi-university consortium, the Hazardous Substance Research Center South and Southwest (1995–2007), while at Louisiana State University and as the Bettie Margaret Smith Chair of Environmental Health Engineering (2004–2013) and director of the Center for Research in Water Resources (2011–2013) at the University of Texas. Dr. Reible was inducted into the National Academy of Engineering in 2005 for his work in identifying management approaches for contaminated sediments. He has led the development of in-situ sediment capping and has evaluated its applicability to a wide range of contaminants and settings, including polycyclic aromatic hydrocarbons from fuels, manufactured gas plants, and creosote-manufacturing facilities; polychlorinated biphenyls; and metals. His current research activities are focused on sustainable water management and the assessment and remediation of contaminated sites. He is a fellow of the American Institute of Chemical Engineers and the American Association for the Advancement of Science. He received his B.S. from Lamar University, and his M.S. and Ph.D. in chemical engineering from the California Institute of Technology.

**Jonathan D. Arthur**, P.G., is the State Geologist of Florida and director of the Florida Geological Survey, a division of the Florida Department of Environmental Protection. Dr. Arthur received his B.S. and Ph.D. from Florida State University and is a fellow of the Geological Society of America. He has served as president of the Association of American State Geologists and the Florida Association of Professional Geologists, and presently serves on the Florida Board of Professional Geologists and the Executive Committee of the American Geosciences Institute. He also served on numerous committees related to restoration of the Florida Everglades. His research has involved aspects of hydrogeology and hydrogeochemistry, including hydrogeologic framework mapping, aquifer vulnerability modeling, and aquifer storage and recovery, the latter with emphasis on water–rock interactions and the fate of metals and metalloids during variable oxidation-reduction conditions. Dr. Arthur was a member of the NRC Committee on Sustainable Underground Storage of Recoverable Water.

**M. Eric Benbow** is an associate professor of entomology at Michigan State University. His research involves basic and applied multiple-scale studies on the biology and ecology of aquatic ecosystems, how terrestrial and aquatic ecosystems are coupled, the influence of human activities on those processes, and microbe–insect interactions in aquatic systems and carrion decomposition. Specific projects include the ecology of microbial–invertebrate interactions and their role in mycobacterial disease emergence in West Africa; microbial–insect carrion interaction networks in watersheds of southeast Alaska; watershed biomonitoring; and carrion decomposition with applications in forensics, including human postmortem microbiome studies. He has studied water withdrawal and watershed development in the tropics, including monitoring how invertebrate communities respond to these impacts. Dr. Benbow has served as a consultant to the World Health Organization on Buruli ulcer, the Republic of Palau for stream bioassessment, and the New Jersey Forensic Science Commission, Forensic Anthropology and Associated Forensic Specialties Subcommittee; as an expert witness in a contested case involving Hawaiian streams; and as an Executive Committee member and former president of the North American Forensic Entomology Association. He received his B.S. and Ph.D. in biology from the University of Dayton.

**Stuart E. G. Findlay** is an aquatic ecologist at the Carey Institute of Ecosystem Studies. Dr. Findlay's research interests encompass characterization and microbial assimilation of dissolved organic carbon in aquatic ecosystems, delivery of carbon from terrestrial to aquatic ecosystems, carbon and nutrient processing in tidal wetlands, and ecosystem functions mediated by submerged aquatic vegetation. He has been conducting research on the Hudson River ecosystem for over 18 years and is interested in watershed restoration issues as well as a variety of approaches to making scientific information more useful for ecosystem management. He received his B.A. in environmental science from the University of Virginia, his M.S. in marine science from the University of South Carolina, and his Ph.D. in zoology from the University of Georgia.

**K. David Hambright** is a professor of biology and director of Environmental Studies at the University of Oklahoma. During the past decade his research has centered on the ecology, evolution, and management of the invasive and toxigenic golden alga *Prymnesium parvum* in lakes and rivers in Oklahoma, Texas, West Virginia, and Pennsylvania. He has recently begun a new long-term research effort aimed at coupling satellite-based remote sensing, digital field photography, and long-term water quality monitoring data on Oklahoman lakes in the effort to develop real-time monitoring capabilities aimed at ensuring public safety on the many public-access recreational lakes in the state. His expertise includes research in climate change and water quality interactions, wetland restoration and habitat and species conservation, paleolimnology, ecosystem modeling, and biodiversity, as well as experience in working with diverse research and modeling teams, interest groups, and stakeholders in politically sensitive systems. He received his B.S. in biology from the University of North Carolina, Charlotte, his M.S. in biology from Texas Christian University, and his Ph.D. in ecology and evolutionary biology from Cornell University.

**Lora A. Harris** is an associate professor at the University of Maryland Center for Environmental Science, based at the Chesapeake Biological Laboratory. She is an estuarine ecologist who applies field and modeling approaches to address important questions regarding nutrient dynamics, primary production, and ecosystem structure and function in a range of estuarine ecosystems. She is interested in climate impacts on estuaries and lagoons, with a particular focus on salt marsh and seagrass ecosystems. Some of her most recent work has involved participatory modeling efforts involving stakeholders and managers seeking solutions to improve water quality and restore seagrasses in Delmarva coastal lagoons and a collaboration with wastewater engineers to understand the restoration trajectories of hypoxic estuaries. Dr. Harris works closely with state and regional agencies in both a research and an advisory capacity. She received her B.S. from Smith College and her Ph.D. from the University of Rhode Island.

**Steve A. Johnson** is an associate professor at the University of Florida. He is a freshwater biologist who focuses on natural resource ecology and the conservation and invasion ecology of amphibians and reptiles. Before joining the University of Florida, he worked as the State Sea Turtle Program Coordinator in North Carolina, and as a research wildlife biologist with the U.S. Geological Survey. At the USGS, he coordinated efforts for the national Amphibian Research and Monitoring Initiative in the southeastern United

States. Dr. Johnson's area of expertise is natural history and conservation of amphibians and reptiles, and he has worked extensively with imperiled species. He is a member of several professional societies, including the Society for Conservation Biology, Herpetologists League, and Wildlife Society. He received his B.S. and M.S. in biology from the University of Central Florida, and his Ph.D. in wildlife ecology and conservation from the University of Florida.

**James A. Rice** is a professor of applied ecology at North Carolina State University. He works mainly with fish, and his research focuses on questions at the interface of basic and applied ecology with the intent to advance knowledge of how aquatic ecosystems function and how to effectively manage and restore them. He employs field studies, experiments, lab analyses, and simulation modeling, and he has worked with a wide variety of organisms and life stages (larval to adult) in systems ranging from ponds, reservoirs, and the Great Lakes to streams, large rivers, and coastal estuaries. Areas of particular interest include predator–prey interactions and food web dynamics in aquatic systems; direct and indirect fish responses to hypoxia; bioenergetics modeling of predation and habitat effects; and impacts and management of introduced species. He received his B.A. in biology from St. Louis University and his M.S. and Ph.D. in zoology from the University of Wisconsin, Madison.

**Kenneth A. Rose** is the France-Merrick Professor in Sustainable Ecosystem Restoration at Horn Point Laboratory of the University of Maryland Center for Environmental Science. Prior to this, Dr. Rose was a professor at Louisiana State University. His current research is focused on modeling population dynamics of fish and aquatic food webs, and how they respond to a variety of types of stressors, including changes in water flows and quality, lethal and sublethal effects of contaminants, hypoxia, alteration of physical habitat, and climate change. He recently published a model of the population dynamics of the delta smelt, which is a listed species in the California Delta that is the center of controversy about how much water can be pumped out of the system for irrigation and water supply. He has also published on lower trophic level (algae and micro and macro zooplankton) food web dynamics. Dr. Rose was a member of review teams for several biological opinions involving delta smelt and salmon. He has served on two National Academies of Sciences, Engineering, and Medicine committees, including the Committee on Sustainable Water and Environmental Management in the California Bay Delta that evaluated the mitigation and conservation actions of biological opinions and the science underlying the short-term and long-term environmental and water usage decision making of the system. He received his B.S. from SUNY Albany and his M.S and Ph.D. in fisheries science from the University of Washington.

**J. Court Stevenson** is professor emeritus at the Horn Point Laboratory of the University of Maryland Center for Environmental Science. His primary areas of interest are coastal zone resources and water quality management issues; ecology of marsh and seagrass systems; effects of sea-level rise on wetlands and coastal shorelines; and the environmental history of Chesapeake Bay and its watershed. He served on the National Academies Committee to Review the St. Johns River Water Supply Impact Study. Dr. Stevenson received his B.S. in biology from Brooklyn College of the City University of New York, and his Ph.D. in botany from the University of North Carolina at Chapel Hill.

**Laura Toran** is the Weeks Chair in Environmental Geology at Temple University in Philadelphia. She has 30 years of experience in modeling and monitoring groundwater. Her recent research activities include using karst springs to understand transport in karst, monitoring urban stormwater and streams, and developing hydrogeophysical techniques to predict groundwater–surface water interaction. She teaches classes in groundwater hydrology including modeling with MODFLOW. She served on the National Research Council Committee on Opportunities for Accelerating Characterization and Treatment of Waste at DOE Nuclear Weapons Sites. Dr. Toran received her B.A. in geology from Macalester College and her Ph.D. in geology from the University of Wisconsin.

## Staff

**Laura J. Ehlers** is a senior staff officer for the Water Science and Technology Board of the National Academies of Sciences, Engineering, and Medicine. Since joining NASEM in 1997, she has served as the study director for more than 20 committees, including the Committee to Review the New York City Watershed Management Strategy, the Committee on Bioavailability of Contaminants in Soils and Sediment, the Committee on Assessment of Water Resources Research, the Committee on Reducing Stormwater Discharge Contributions to Water Pollution, and the Committee to Review EPA's Economic Analysis of Final Water Quality Standards for Nutrients for Lakes and Flowing Waters in Florida. Dr. Ehlers has periodically consulted for the U.S. Environmental Protection Agency's Office of Research Development regarding their water quality research programs. She received her B.S. from the California Institute of Technology, majoring in biology and engineering and applied science. She earned both an M.S.E. and a Ph.D. in environmental engineering at the Johns Hopkins University.