Appendix O
NAS Report 1 and Phase 2 Study Announcement

1 *Review of the Edwards Aquifer Habitat Conservation Plan: Report 1*

2 Study Announcement: Review of the Edwards Aquifer Habitat Conservation Program – Phase 2

Appendix O1

Review of the Edwards Aquifer Habitat Conservation Plan: Report 1

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Review of the Edwards Aquifer Habitat Conservation Plan: Report 1

Committee to Review the Edwards Aquifer Habitat Conservation Plan

Water Science and Technology Board

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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COMMITTEE TO REVIEW THE EDWARDS AQUIFER HABITAT CONSERVATION PLAN

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K. DAVID HAMBRIGHT, University of Oklahoma, Norman
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KENNETH A. ROSE, Louisiana State University, Baton Rouge
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GREG D. WOODSIDE, Orange County Water District, Fountain Valley, California

NRC Staff

LAURA J. EHLERS, Study Director, Water Science and Technology Board
MICHAEL J. STOEVER, Research Associate, Water Science and Technology Board

Preface

The nation's groundwater is a precious resource that is sensitive to overuse, drought, and contamination. In many areas of the country the population depends upon that resource for water to drink, water to grow food, and water to support the commercial and industrial activities that drive the economy. Ecosystems, also depend upon that resource, particularly where surface waters and groundwaters are closely linked. At times there is competition between human and ecological needs for those waters and it is difficult to balance their competing interests.

The Edwards Aquifer in south-central Texas is just such a groundwater resource. It is the primary source of water for one of the fastest growing cities in the United States, San Antonio, and it also supplies irrigation water to thousands of farmers and livestock operators. The Edwards Aquifer also is the source water for several springs and rivers, including the two largest freshwater springs in Texas that form the San Marcos and Comal Rivers. The unique habitat afforded by these spring-fed rivers has led to the development of species that are found in no other locations on Earth. Due to the potential for variations in spring flow caused by both human and natural causes, these species are continuously at risk and have been recognized as endangered under the federal Endangered Species Act (ESA). In an effort to manage the river systems and the aquifer that controls them, the Edwards Aquifer Authority (EAA) and stakeholders have developed a Habitat Conservation Plan (HCP). The HCP seeks to effectively manage the river–aquifer system to ensure the viability of the ESA-listed species in the face of drought, population growth, and other threats to the aquifer. Although implementation of the HCP resides primarily with the EAA, a broad group of stakeholders plays a role in the management of the Edwards Aquifer.

The National Research Council (NRC) was asked to assist in this process by reviewing the activities around implementing the HCP. The NRC 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 ESA-listed species. Thus, the current report is focused specifically on a review of the hydrologic modeling, the ecological modeling, the water quality and biological monitoring, and the Applied Research Program. The fundamental question that this report addresses is whether the scientific initiatives appropriately address uncertainties and fill knowledge gaps in the river-aquifer system and the species of concern. It is hoped that the successful completion of these scientific initiatives will ultimately lead the EAA to an improved understanding of how to manage the system and protect these species.

Several topics that might be expected in this initial report are in fact going to be the subjects of subsequent reports. Thus, the current report does not evaluate the process of

implementation of the HCP nor provide judgments on the policy of how the river-aquifer system should be managed. The report also does not evaluate the performance of minimization and mitigation measures currently in place, as this will be tackled in the second report. Finally, the report does not evaluate the adequacy of the goals and objectives of the HCP to protect the endangered species, as this will occur in the final report. Rather, this report evaluates whether the data are being developed that will allow a later determination of the adequacy of the goals and objectives.

The NRC constituted the Committee to Review the Edwards Aquifer Habitat Conservation Plan in early 2014—12 individuals representing expertise in all areas relevant to the Statement of Task, including the hydrogeology of the aquifer and the physics, chemistry, and biology of river systems. Four committee meetings were held during 2014. The first two meetings were held in San Antonio, Texas, and included presentations on current activities relevant to the project. We 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 EAA Habitat Conservation Program, EAA; Jim Winterlee, EAA; Mark Hamilton, EAA; Ed Oborny, BIO-WEST; Bob Hall, EAA; George Ward, University of Texas; Ron Green, Southwest Research Institute; Geary Schindel, EAA; Bill Grant, University of Texas; Todd Swannack, Engineer Research and Development Center; Thom Hardy, Texas State University; and members of the Science Committee (Doyle Mosier, Chair; Miguel Acevedo, University of North Texas at Denton; Tom Arsuffi, Texas Tech University; Janis Bush, University of Texas at San Antonio; Jacquelyn Duke, Baylor University; Charlie Kreitler, LBG-Guyton Associates; Glenn Longley, Texas State University; Robert Mace, Texas Water Development Board; Chad Norris, Texas Parks and Wildlife Department; Jackie Poole, Texas Parks and Wildlife Department; Floyd Weckerly, Texas State University). 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; Thom Hardy, Texas State University; and Melanie Howard, City of San Marcos. These trips were invaluable to increasing the Committee's understanding and appreciation of these unique spring systems.

Although committee members represented many diverse perspectives, we 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 Edwards Aquifer and protection of the ESA-listed species.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for 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 wish to thank the following individuals for their review of this report: James J. Anderson, University of Washington; John D. Bredehoeft, The HydroDynamics Group; Stephen R. Carpenter, University of Wisconsin-Madison; Mary C. Freeman, USGS Patuxent Wildlife Reserve; Wendy D. Graham, University of Florida and the University of Florida Water Institute; Lora A. Harris, University of Maryland Center for Environmental Science; Rita P. Maguire, Maguire & Pearce, PLLC; Judith L. Meyer,

University of Georgia (retired); Stavros S. Papadopulos, S. S. Papadopulos & Associates, Inc.; and Carol M. Wicks, Louisiana State University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report 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 NRC, 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 and the institution.

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 United States. The aquifer, which contains over 25,000,000 acre-feet of useable water, is the primary source of drinking water for over 2.3 million people in San Antonio and surrounding communities. It also supplies irrigation water to thousands of farmers and livestock operators in the region. Given its karst hydrogeology, the Edwards Aquifer is extremely responsive to both rainfall and to withdrawals (e.g., pumping for irrigation and water supply), such that large volumes of groundwater are rapidly transported through the system.

The two largest freshwater springs in Texas—Comal Springs and San Marcos Springs—emanate from the Edwards Aquifer and currently account for about 45 percent of its annual discharge (withdrawals like pumping account for the other half). These springs and their associated river systems are heavily used for recreation and are also home to a number of endemic species found nowhere else in the world. Because of the potential for reduced flows to the springs during times of drought, eight of these species are listed under the federal Endangered Species Act: the fountain darter, the San Marcos gambusia (presumed extinct), the Texas blind salamander, the Comal Springs dryopid beetle, the Comal Springs riffle beetle, Peck's Cave amphipod, Texas wild rice, and the San Marcos salamander. To protect the listed species, the Edwards Aquifer Authority (EAA) and four other local entities applied for an Incidental Take Permit under the Endangered Species Act, creating a 15-year comprehensive Habitat Conservation Plan (HCP) as part of the process.

Central Texas is currently experiencing drought conditions, although not as severe as the drought of record in the 1950s, during which flows at Comal Springs ceased for four months and flows at San Marcos Springs were severely reduced. At current pumping levels, a similar drought today would be catastrophic to the ESA-listed species of the Edwards Aquifer and its springs. Given the uniqueness of these ecosystems, the many diverse projects that make up the HCP, and the persistence of drought conditions across the region, the EAA has requested the input of the National Research Council as the HCP is implemented. This report is the first product of a three-phase study to provide advice to the EAA on various scientific aspects of the HCP that will ultimately lead to its adaptive management in Year 7.

The National Research Council was charged with constituting a committee of experts that would review and provide advice on four scientific initiatives within the HCP: (1) ecological modeling, (2) hydrologic modeling, (3) biological and water quality monitoring, and (4) applied research. In particular, the Committee's first report addresses:

- hydrological and ecological modeling approaches;
- accuracy and reliability of the assumptions used to support development of both conceptual and quantitative models;

- adequacy of data for model calibration and verification;
- identification and description of uncertainties;
- additional monitoring data needs;
- additional research needs; and
- other issues deemed relevant by the Committee.

Later reports will review the performance of minimization and mitigation measures found in the HCP, including the four spring flow protection measures, as well as the adequacy of the biological goals and objectives to protect the endangered species.

Chapter 2 of this report addresses the hydrologic modeling, reviewing both the updates to the MODFLOW model and the creation of a finite element model of the aquifer. It tackles the issues of how to represent recharge and conduits in the modeling and how to conduct uncertainty analysis. Chapter 3 describes the state of ecological modeling for Comal and San Marcos Springs, focusing on fountain darter, submersed aquatic vegetation, Texas wild rice, and the Comal Springs riffle beetle. Chapter 4 evaluates the water quality monitoring program and the biomonitoring program, making recommendations for what should continue to be sampled and whether the biomonitoring program can provide the necessary data and information for the ecological modeling. Chapter 5 critiques the Applied Research Program, which is populated with projects intended to either inform the ecological modeling or fill knowledge gaps about the listed species. The final chapter tackles overarching issues, such as the need for data management and integration within the HCP, performance monitoring of minimization and mitigation measures, and worst-case scenarios to be considered.

HYDROLOGIC MODELING

The primary objectives of the hydrologic modeling are to create a groundwater model that can reproduce known spring flows and then to use this model to predict (1) the effects of potential future hydrologic conditions (such as climate change and droughts) on spring flow, and (2) how management actions (like conservation measures) will affect water levels and spring flows.

The Edwards Aquifer's unique hydrogeology, which is characterized by significant heterogeneity in both porosity and permeability and physical features such as conduits, faults, and barriers, complicates modeling efforts. There have been many efforts to characterize and model the Edwards Aquifer, most based on the popular MODFLOW code. The hydrologic modeling activities that are the subject of the Chapter 2 review include updates to the MODFLOW model, creation of a new finite element model of the aquifer, better aquifer characterization and delineation of boundary conditions, development of new methods for determining recharge, and uncertainty analysis.

The hydrologic modeling effort has shown continuous improvement in both the use of models and the incorporation of new data. The EAA is to be commended for its progress to date. Listed below are areas that merit further attention and recommendations for future work that will build upon the EAA's strong foundation of modeling and data collection efforts.

The EAA could gain efficiency by moving toward a single model that incorporates the best concepts from existing modeling efforts. Continued development of "competing" models (i.e., having both a MODFLOW model and a finite element model) is inefficient and unnecessary and cannot be used for assessing model uncertainty. Any new model selected should have features that benefit and advance the conceptual model, such as telescoping meshes (to accommodate shorter time scales) and linear features for conduits and barriers.

Model uncertainty needs to be quantitatively assessed and presented in formal EAA documents. Quantifying model uncertainty increases a model's defensibility and can provide a reasonable estimate of model error, which is important information when using a model for management decisions. Uncertainty has been mentioned in some of the EAA's modeling reports but is not a standard feature in its documentation of modeling results, including presentations to the Committee. Specific recommendations include conducting more explicit sensitivity analysis; validating the groundwater model by testing its predictive abilities using data from a time period not included in the model calibration; using additional calibration and validation metrics; and having confidence intervals presented with all modeling results.

ECOLOGICAL MODELING

A major activity within the HCP is the development of new ecological models that will be able to predict species population metrics under a variety of potential future conditions. The primary threat to the ESA-listed species in the major springs of the Edwards Aquifer is the loss of habitat from reduced spring flows, which could occur as the combined result of fluctuating rainfall, regional pumping, and subsequent drawdown of the aquifer. Other threats include increased competition and predation from non-native species, direct or indirect habitat destruction or modification by humans (e.g., recreational activities), and other factors such as high nutrient loading and bank erosion that negatively affect water quality.

Three of the endangered species—the fountain darter, the Comal Springs riffle beetle, and Texas wild rice—have been designated as indicator species within the HCP and, along with submersed aquatic vegetation, are the initial targets of modeling efforts, including both habitat suitability analyses and predictive ecological models. In general, the approach to ecological modeling of combining field data, habitat suitability analyses, and a population dynamics model is appropriate and can support the management decisions that will need to be made as the HCP proceeds. There are, however, several aspects of the analyses that should be adjusted to ensure that robust conclusions are obtained.

The goal of the submersed aquatic vegetation modeling, which is in its early stages, should be clarified. Whether the goal is to simulate submersed aquatic vegetation biomass dynamics or to simulate habitat for the fountain darter model will affect how many models are needed and how each model is formulated and tested. Similarly, key issues about spatial resolution and whether to model individual species or a "generic" species depend on the goals of the modeling.

Given the absence of a planned ecological model for Texas wild rice, the current habitat suitability analysis should be treated as an hypothesis and tested for robustness throughout the San Marcos River. The EAA should consider designing minimization and mitigation measures for Texas wild rice in a manner to provide experimental analysis of the habitat suitability results. For example, the minimization and mitigation activities could be used to test the validity of using water depth and velocity as the only predictive variables for optimal habitat for Texas wild rice. Similarly, one could use replicated reference and control areas to provide explicit tests of the efficacy of replanting and to quantify the roles of discharge, competition, and other factors that may limit Texas wild rice growth and survival.

The individual-based model for fountain darter is a scientifically sound approach for modeling population dynamics that will require extensive data for model formulation, calibration, and validation. Suggestions for improving the modeling effort include (1) hosting workshops at key times (to define the questions, formulate the model, and present preliminary results), (2) making clearer links between the monitoring data and the Applied Research projects and how both will be used to inform the modeling, and (3) engaging modelers with experience in developing similar individual-based models. Given the complexity inherent in the modeling effort, the habitat suitability analyses done for fountain darter could act as a "back-up" to the ongoing individual-based modeling and provide additional quasi-independent results.

If the Comal Springs riffle beetle is to be an adequate indicator of some of the other ESA-listed species, it is critical to have a much deeper understanding of its spatial distribution, range of potential habitats, and natural history. Although the HCP has identified the beetle as a primary species for monitoring and calls the beetle an indicator of other species that are not being monitored, the degree to which it is a reliable indicator is presently not well understood nor has it been objectively tested.

It is recommended that as a top priority the EAA develop an ecosystem-based conceptual model, or a series of models of increasing resolution, that show how water quality and quantity, other biota, and restoration and mitigation activities are expected to interact with the indicator species, as well as with all covered species. Boxes in the conceptual model would represent targets of the monitoring program, while arrows linking the boxes would represent quantitative or empirically derived relationships between the boxes based on research. Such interactions for which too little data are available to establish empirical relationships could be targeted for monitoring and further research during the permit period.

MONITORING

The HCP requires the development and implementation of a monitoring plan to (1) evaluate compliance; (2) determine if progress is being made toward meeting the long-term biological goals and objectives; and (3) provide scientific data and feedback information for the adaptive management process. This report focuses on the biomonitoring and water quality monitoring programs, two somewhat independent programs intended to provide the

observational data needed to assess whether the HCP is meeting its goals of protecting the target species as well as collecting the ancillary biological community and water quality data required to identify plausible mechanisms for observed changes in the target species abundance or distribution.

The monitoring of physical, chemical, and biological characteristics of the Comal and San Marco Spring and River systems has been ongoing since 2000 and is now even more comprehensive as a result of the HCP. While in general the Committee found the monitoring programs to be strong, it also identified areas for improvement.

The monitoring programs do not provide a clear mechanism to scale results to the entire spring and reach system because none of the sampling locations were selected using randomization procedures. Despite some sampling sites being labeled as "representative," it is inappropriate to use observations derived from these sampling locations to make inferences about the entire river or spring systems. The term "index site" would more accurately describe these locations. Monitoring of index sites needs to continue in order to assess trends and build on existing databases. If the EAA finds it is necessary to provide system-wide estimates of population densities of target species rather than relying on trends at index sites, it will need to invoke special studies or conduct sampling using randomization techniques.

Enhanced sampling for nutrients is recommended. The presence of annual algal blooms and the importance of aquatic macrophytes in structuring fish and macroinvertebrate communities suggest that nutrient loading plays an important role in the spring and river systems. The current detection limits for soluble reactive phosphorus, NO_3/NO_2, and total nitrogen are so high that significant changes in nutrient concentrations could go undetected. If the detection limits for phosphorus species, NO_3/NO_2, and total nitrogen were reduced to 2, 10, and 50 micrograms/liter, respectively, by changing analytical methods, this would enable identification of nutrient concerns in both spring systems.

New quantitative sampling methods are needed for the Comal Springs riffle beetle to complement and improve upon the current method (the cotton lure approach). At the same time, a large-scale stratified random survey of the potential habitat available in both systems would provide more robust data on how flow variation or sedimentation affects the habitat and thus population numbers of the Comal Springs riffle beetle. The comprehensive survey of beetle distribution proposed as part of the Applied Research Program should be given high priority.

APPLIED RESEARCH PROGRAM

Critical to the recovery and protection of all aquifer species is knowledge of the species-specific demography and ecology, including knowledge of natural population fluctuations. At the present time, there is considerably more knowledge about fountain darters and Texas wild rice than about the Comal Springs riffle beetle and most of the other ESA-listed species. The

Applied Research Program is intended to fill knowledge gaps about the endangered species in the Comal and San Marcos systems, particularly under low flow conditions, and to provide data and information that can be used to parameterize and validate the ecological models. The overall goal of the program is to generate useful information early on to be able to make well-informed decisions about the direction of the HCP in Year 7. Chapter 5 evaluates the projects that have been funded to date, most of which were useful for providing data and information to the ecological modeling efforts. The following paragraphs describe new study topics that should be considered for inclusion in the Applied Research Program.

Fountain Darter: Additional studies on fountain darter movement would be beneficial to the ecological modeling effort, preferably allowing for Lagrangian tracks to be estimated. A second set of special studies could confront the persistent lack of a relationship found between flow and fountain darter metrics. While the flow-triggered sampling is a good idea, these measurements could be further supported by studies that use lab and field measurements to ensure responses are recorded over a range of flows. A third issue is obtaining measurements related to individual fountain darter health that go beyond the densities and lengths of individuals measured in the current biomonitoring, such as variations on the classic condition index and non-lethal estimation of tissue composition.

Comal Springs Riffle Beetle: Most critical for the beetle is gathering information on life history, life cycle, and spatial distribution. This includes information on densities of both immature and adult life stages throughout the year, growth rates of the life stages, how many generations occur each year and if they are synchronous, how fast the life cycle proceeds, and how the life cycle and other life history attributes like fecundity might be affected by changing flow or sediment conditions. While generating such information is formidable in the short-term, now is the time to establish such long-term research goals if a population model for the beetle is an objective of the HCP.

Submersed Aquatic Vegetation: New Applied Research projects for submersed aquatic vegetation should address the needs of the modeling efforts by focusing on supplying data on submersed aquatic vegetation growth, dispersal, and recolonization for those species that are the best habitat for fountain darter. Studies that could elucidate the interactions between submersed aquatic vegetation and the fountain darter would be particularly helpful.

Nutrients: There is an abundance of nutrients in the two spring systems, as indicated by the annual summer green algal blooms in the Upper Spring Run reach of the Comal River. Anecdotal evidence suggests that the blooms tend to accompany low flows and high temperatures. It would prove highly beneficial to have a better understanding of the nutrient budgets in the two spring systems. In addition to the physical impacts of low flow, there could be very important indirect effects of low flow on the overall productivity and food web dynamics of the spring and river ecosystems caused by nutrients.

Beyond considering new research topics, the Applied Research Program could be restructured to help to ensure that the limited funds available for the program target priority research needs to support the ecological modeling efforts and the success of the HCP more generally. The following structural modifications to further increase the usefulness and efficiency of the current program are recommended.

The Applied Research Program would benefit from a more transparent process for prioritizing and funding all applied research projects that includes stakeholder involvement, for example through the Science Committee, and peer review.

The Applied Research Program would benefit from greater competition and collaboration with outside scientific experts through open and widely disseminated solicitations for research. Increasing the diversity of thought, understanding, and perspective will serve to strengthen the HCP and increase the likelihood that project goals will be met.

The program should offer some longer (e.g., two- to five-year) projects in order to maximize interest and collaboration from the region's leading researchers. Multiple-year project proposals can be awarded with the simple limitation that funding in subsequent years is contingent on funding availability, project needs, and project success.

OVERARCHING ISSUES

The EAA and other Permittees are at the beginning stages of implementing a complex HCP and are doing an excellent job in most respects. Nevertheless, there are a number of overarching concerns regarding the implementation process that may hinder the later stages of the HCP, especially any future attempts to renew the HCP and the Edwards Aquifer Incidental Take Permit.

First, **the HCP would benefit from more formal integration to enable clear explanation of the many sets of results emanating from the monitoring, modeling, and research efforts.** Without greater attention to project integration, there is a danger that the large number of separate projects will not combine seamlessly into an overall science program. Several steps could be taken to enhance integration of the HCP. As mentioned previously, an overall conceptual model of the system including hydrological, climate, and biological community components could guide the development of quantitative modeling of sub-components, identify gaps in understanding, and provide context for understanding the responses of particular species of interest. A second way to achieve integration would be to develop a comprehensive data/information management system. Such a system would ensure both internal and external access to relevant data, facilitate data analyses and syntheses across multiple data types and sources, buffer against the potential turnover of key personnel, and increase transparency and communication across stakeholders. Finally, the EAA could convene an annual science meeting to discuss results, discover gaps in understanding, and help plan future activities. Ideally, such a meeting would include all project and contract scientists, other university and agency scientists who might be interested in becoming involved in future studies, and various stakeholder groups.

The second overarching issue is the need to **monitor the performance of the many minimization and mitigation measures currently being implemented**, including recreational control, removal of exotics, riparian restoration and bank stabilization, and replanting of Texas wild rice. Although these measures are not the primary focus on this report, the Committee feels it is critical for the EAA to commence performance monitoring as soon as possible.

Third, **the Committee recommends that the EAA undertake more formal and rigorous statistical analyses of its laboratory and field data.** Much of the data found in documents supporting the HCP do not include error bars or other measures that demonstrate the variability of the data or the uncertainty of model predictions. More formal statistical analysis, such as the incorporation of variance into estimated means and other summary statistics, would give additional credibility to the scientific basis of the HCP. There is significant opportunity for exploring the key field datasets and model results, both ecological and hydrological, with more advanced statistical methods than simple summary statistics and graphical plotting.

Finally, there is a prevailing assumption within the HCP that relevant legal and ecological conditions will remain relatively stable throughout the Plan's 15-year implementation period. However, this may not be the case and therefore t**he Committee recommends that the EAA begin to think now about possible worst case scenarios and their potential implications for both modeling and HCP implementation.** On the modeling side, the Permittees should consider whether the models currently being developed rest on ecological assumptions that could be altered by a changing climate and, if so, whether potential or predicted alterations can themselves be incorporated into the model. On the implementation side, considering potential future changes now could allow the Permittees to develop contingency plans—ecological, political, or legal—for future "worst case" scenarios, building adaptability, flexibility, and resilience into the execution of the HCP. Examples of potential future "worst case" scenarios worth considering are:

- increased groundwater pumping from exempt/unregulated wells that undermines the HCP's minimum flow requirements;
- drought conditions that exceed the drought of record from the 1950s;
- climate change impacts become significant faster than expected;
- high court affirmation of the *Bragg* constitutional takings decision; and
- subjugation to Aransas National Wildlife Refuge ESA issues.

These scenarios and others, along with their implications to the HCP, are described in detail in Chapter 6.

1

Introduction

The Edwards Aquifer is located in south-central Texas and is one of the most productive karst aquifers in the United States. It underlies several Texas counties, covering an area about 180 miles long and from five to 40 miles wide (see Figure 1-1). It is the primary water source for the growing city of San Antonio and its surrounding communities, home to over 2.3 million people. Many of these cities (Uvalde, San Antonio, New Braunfels, and San Marcos) were originally founded around the large springs that discharge from the Edwards Aquifer. The aquifer also 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 annual water withdrawals from the aquifer system.

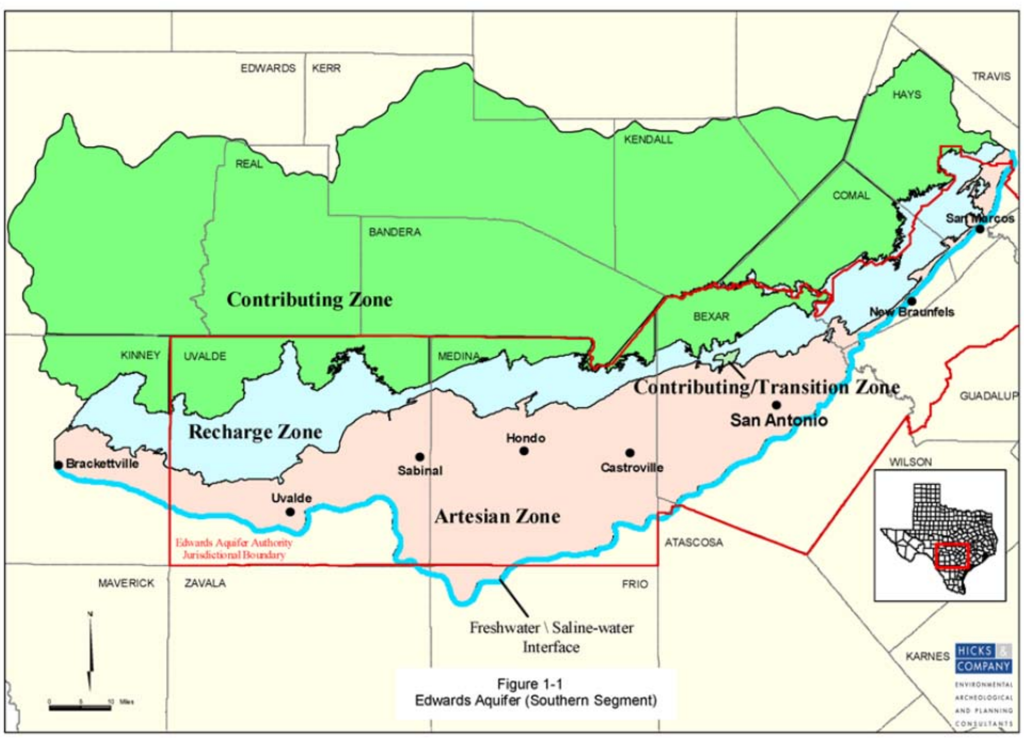

FIGURE 1-1 The Edwards Aquifer, showing the jurisdiction of the Edwards Aquifer Authority. SOURCE: Figure 1-1 from EARIP (2012).

In addition to providing drinking water for many communities, the Edwards Aquifer supplies several springs, including the two largest freshwater springs in Texas—Comal Springs in New Braunfels and San Marcos Springs in San Marcos. Many people use these springs and their associated river systems for recreation, but they are also home to a number of endemic species of fish, amphibians, insects, and plants found nowhere else. Because of the potential for reduced spring flow during times of drought, seven of these species are listed under the federal Endangered Species Act (ESA) as endangered species: the fountain darter, the San Marcos gambusia (presumed extinct), the Texas blind salamander, the Comal Springs dryopid beetle, the Comal Springs riffle beetle, Peck's Cave Amphipod, and Texas wild rice. One other species, the San Marcos salamander, is federally listed as threatened, and the U.S Fish and Wildlife Service is currently deciding whether to list three other species in the system in response to citizen petitions.

The hydrology of the Edwards Aquifer allows for the extremely high yield wells and springs in the system (see subsequent section on Water Budget), with large volumes of groundwater being transported through the system very quickly, on the order of days. Indeed, in some parts of the Edwards Aquifer, groundwater velocities exceed two miles per day (Johnson et al., 2012). As a result, the aquifer responds quickly both to rainfall events (known as recharge) and to withdrawals, such as pumping for irrigation and water supply. During the 1950s, central Texas experienced what is now called the "drought of record," the most severe drought recorded for the region. During this drought, flows at Comal Springs ceased for four months and flows at San Marcos Springs were severely reduced. At current pumping levels, a similar drought today could result in complete cessation of flow at Comal Springs for more than three years and near cessation of flow at San Marcos Springs (EARIP, 2012). Such reductions in spring flow would be catastrophic to the ESA-listed (and other) species living in the Edwards Aquifer and its springs. As discussed later in this chapter, climate change in this region may potentially increase the risk of such drought events, exacerbating the future threat to these species.

To protect the ESA-listed species, the Edwards Aquifer Authority (EAA) and four other local entities applied for an Incidental Take Permit under the ESA, creating a 15-year Habitat Conservation Plan as part of the application process. The EAA is a regional government body tasked with managing domestic, industrial, and agricultural withdrawals from the Edwards Aquifer while maintaining spring flows at quantities that can support recreation and ESA-listed species. Among other duties, the EAA implements the Habitat Conservation Plan, which the U.S. Fish and Wildlife Service (FWS) finalized and approved in 2013 after a years-long development process.

Despite the high yields of the Edwards Aquifer, increased pumping and other uses of Edwards Aquifer water pose significant threats to the listed species at Comal and San Marcos Springs. Given the uniqueness of these two ecosystems, the many diverse projects that make up the Habitat Conservation Plan, and the persistence of drought conditions across the region, the EAA has requested the input of the National Academy of Sciences as it (the EAA) implements the Habitat Conservation Plan. This report is the first product of a three-phase study to provide advice to the EAA on various scientific aspects of the Habitat Conservation Plan that will ultimately lead to improved management of the aquifer.

THE EDWARDS AQUIFER

Because the major impacts to endangered species residing in the springs and river systems of the Edwards Aquifer are believed to be related to flow reductions, this section focuses on aquifer physiography and hydrology, regional climate, and the water budget. Local water quality impacts from changes in land use and land cover are thought to be of secondary importance to the springs and are discussed in Chapter 4.

Physiography and Hydrology

The Edwards Aquifer is a karst aquifer that spans three major physiographic zones: the Edwards Plateau, the Balcones fault zone (system), and the Gulf Coastal Plain. The Balcones fault zone is the principal focus of the Habitat Conservation Plan. Along this fault system, the Edwards Aquifer is highly productive, with high-capacity water wells and high spring discharges. In addition, at least six springs occur within this zone, including two first magnitude springs (i.e., flows are at least 100 cubic feet per second or CFS), the San Marcos and Comal.

The Edwards Aquifer is subdivided into four zones reflecting hydrologic function (see Figure 1-1). Contributing and recharge zones lie largely to the north of the aquifer, while pumping and artesian wells occur largely over and to the south of the aquifer. The *contributing zone*, which is also known as the drainage area or the catchment area, includes 5,400 square miles and represents areas where rainfall is directed by streams toward the recharge zone. The catchment zone lies within the Edwards Plateau, also known as the Texas Hill Country, and includes elevations ranging from 1,000 to 2,300 feet above sea level. The *recharge zone* of the Edwards Aquifer is approximately 1,250 square miles. This zone reflects the area where precipitation percolates and flows into the groundwater to replenish the aquifer. The zone extends along the central east-west axis of the aquifer and is generally unconfined, with exposures of the Edwards Limestone along the Balcones fault system. Recharge occurs through dissolution-enhanced features, including faults, fractures, bedding planes caves, and conduits. Surface streams become sinking streams (or swallets) in the recharge zone. Recharge within this zone is a function of overland drainage from the contributing zone and reflects volumes remaining after precipitation and infiltration in the contributing zone as well as losses resulting from evapotranspiration.

The *artesian zone* encompasses 2,650 square miles and comprises the region in which the Edwards Aquifer is under artesian conditions, meaning that pressure levels in the aquifer cause water levels in wells to rise to elevations above the top of the aquifer. The Edwards Aquifer in this area is generally under confined conditions, where a regional clay-rich unit called the Del Rio Clay occurs on top of the carbonates of the Edwards Aquifer. Where these confined conditions exist, which maintain pressure in the aquifer, groundwater flow from the aquifer to land surface locally occurs in the form of springs and seeps.

The Edwards Aquifer underlies approximately 4,000 square miles in 18 counties and ranges to more than 900 feet thick (Lindgren et al., 2004). Three hydrogeological segments have been delineated within the Edwards Aquifer: the southern (San Antonio) segment, the Barton Springs (Austin) segment, and the northern segment (Figure 1-2). A groundwater divide in the vicinity north of San Marcos Springs in Hays County separates the San Antonio segment from

the Barton Springs segment. Under most hydrologic conditions, groundwater from the San Antonio and Barton Springs segments does not mix; however, during drought conditions there is potential for water to bypass San Marcos springs and flow north to the Barton Springs segment (HDR, 2010). The Colorado River hydrologically separates the Barton Springs segment from the northern segment. Comal and San Marcos Springs are located within the San Antonio segment of the Edwards Aquifer, which spans approximately 3,600 square miles and is the focus of the Habitat Conservation Plan and this report.

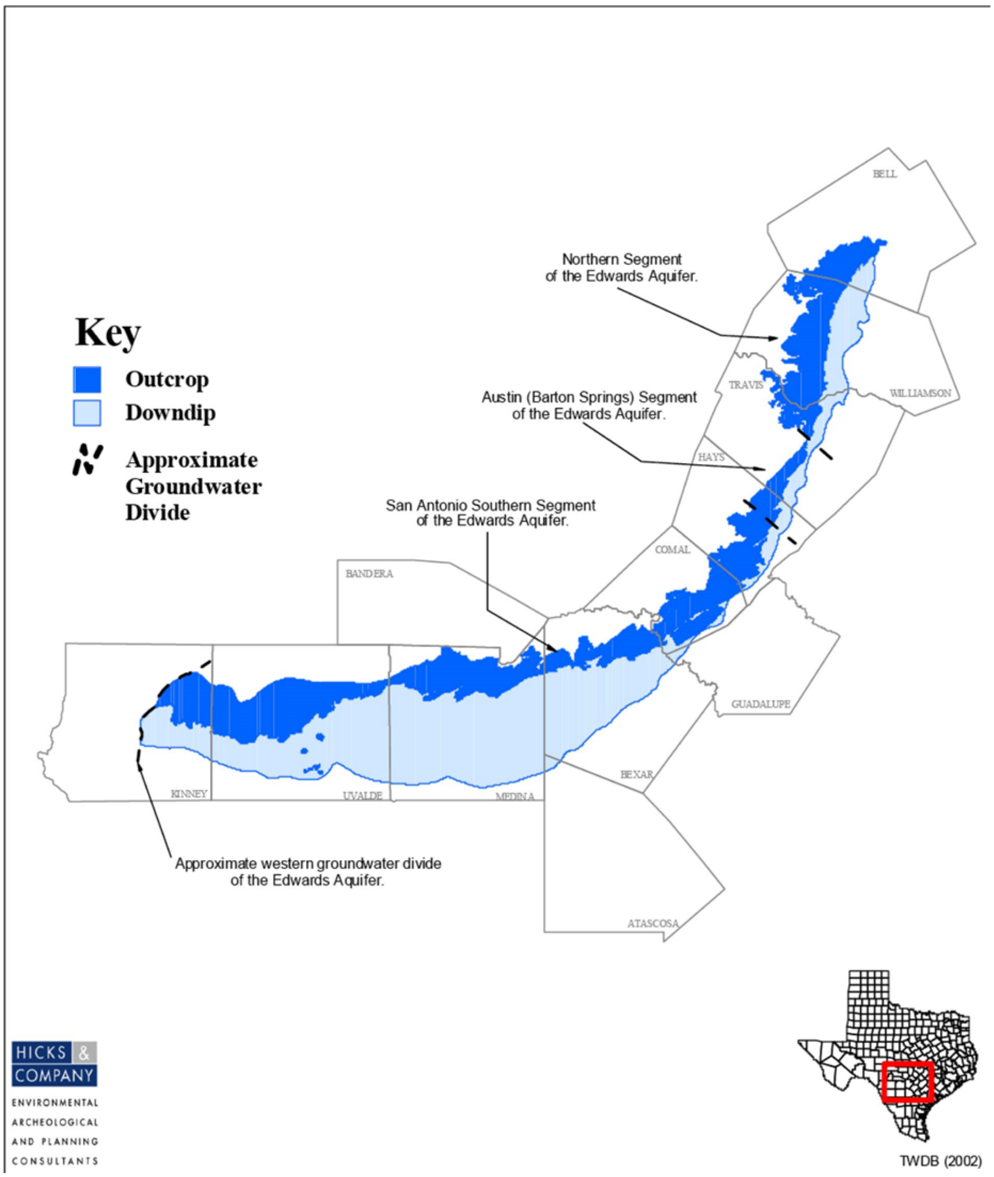

FIGURE 1-2 Segments of the Edwards Aquifer recharge and artesian zone.
SOURCE: Figure 3-16 from EARIP (2012).

One important boundary in the Edwards Aquifer system is the southern boundary, which is defined by the freshwater/saltwater transition zone as demarcated by the 1000 mg/L total dissolved solids (TDS) concentration line. Saltwater intrusion into the artesian zone is one of the risks that pumping of the Edwards Aquifer poses to the system. It is for that reason that the Edwards Aquifer Data Collection Program includes salinity monitoring at 11 wells. Water level elevations collected from index well J-17 correlate strongly with those from the salinity monitoring wells. As shown in Figure 1-3, while J-17 water levels have fluctuated by more than 30 feet, no trend between water levels and TDS levels has been observed, indicating that the salinity concentrations are not sensitive to water levels over the observed period of record.

The geological composition and history of the Edwards Aquifer provides for a complex groundwater flow system. Soluble carbonate rocks, such as limestones, comprise the aquifer rocks and give rise to karst features, such as springs, caves and sinkholes. Tectonic stresses in the geologic past have produced faults and fractures. Groundwater flowing along these features can dissolve the rock and increase their role in groundwater movement through the system. In addition, groundwater flows through the microscopic connected pore spaces (permeability) in the limestones. This triple-permeability nature of the Edwards Aquifer—matrix, karst, and fracture flow—contributes to vast local differences in groundwater flow regimes. In some areas, flow is intergranular and slow, whereas in other areas, the aquifer is highly responsive to changes in pressures, or hydraulic head, because of conduit or fracture flow. Because of the highly karstic nature of the Edwards Aquifer, much of its recharge is rapid and unfiltered, making it is highly vulnerable to surface sources of contamination. Movement of groundwater in the Edwards aquifer is generally from west to east to northeast.

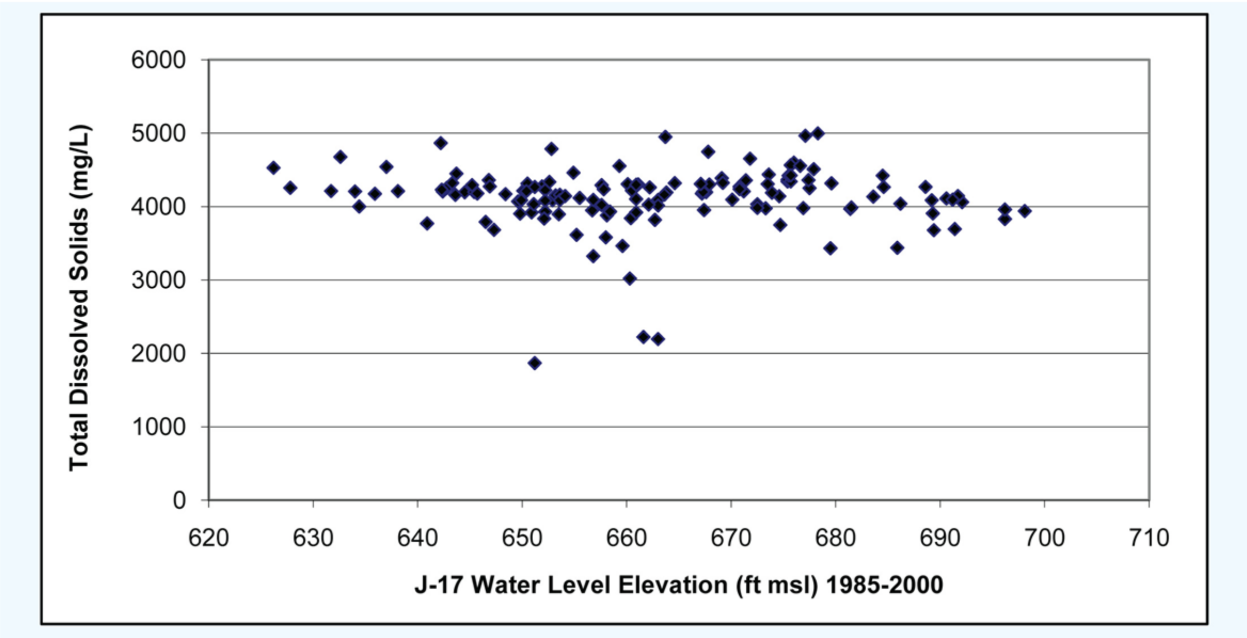

FIGURE 1-3 Total dissolved solids as a function of water level in the J-17 index well.
SOURCE: Johnson et al. (2009).

Climate

Precipitation

More than a foot of variability occurs in precipitation across the Edwards Aquifer region (Figure 1-4), with annual precipitation values ranging from approximately 22 inches in the western extent to over 34 inches in the eastern extent. The mean annual precipitation for San Antonio from 1934 through 2013 is approximately 30.38 inches, although annual precipitation may vary from year to year by more than 20 inches.

Figure 1-5 demonstrates this variability for the San Antonio area. Periods of high rainfall (in excess of 40 inches per year) are separated by periods of drought, the most significant having occurred from 1950 to 1956, during which time precipitation was well below the mean annual average of 30.38 inches for six concurrent years. This period is recognized as the "drought of record" and coincides with a 144-day cessation of flow at Comal Springs in 1956 (Longley, 1995).

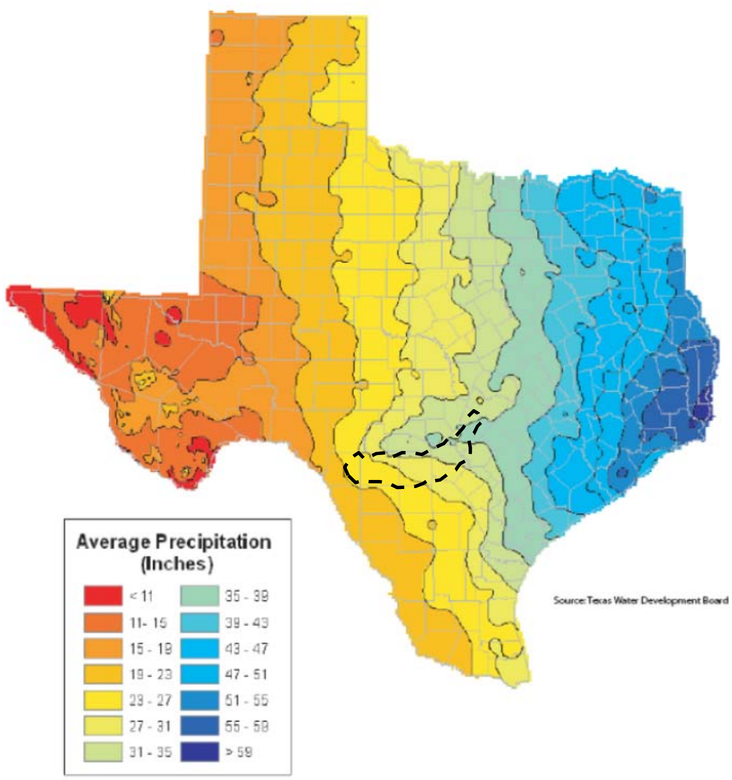

FIGURE 1-4 Average annual precipitation 1971-2000. The dashed black line outlines the Edwards Aquifer region.
SOURCE: Adapted from Figure 3-3 in EARIP (2012).

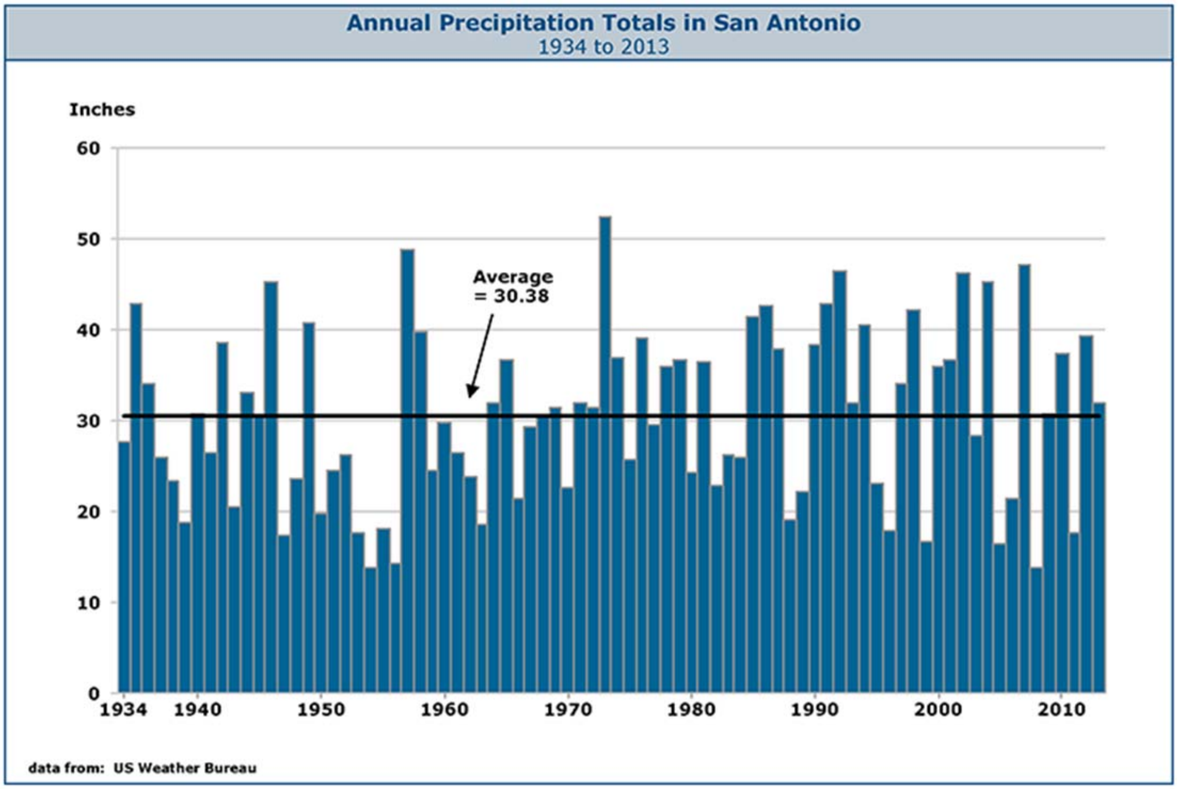

FIGURE 1-5 Annual precipitation in San Antonio, Texas.
SOURCE: Edwardsaquifer.net (accessed October 23, 2014).

Evapotranspiration

Evapotranspiration along the extent of the Edwards Aquifer ranges from more than 60 inches per year in the western extent to 30 inches per year in the eastern extent (Scanlon et al., 2005). Moving westward across the region, evapotranspiration increasingly exceeds precipitation, reaching an annual average difference of more than 30 inches in the western-most area. This pattern declines and slightly reverses moving eastward across the Edwards Aquifer region, such that average annual precipitation exceeds evapotranspiration by more than five inches in the most eastern area. Comparison of the two parameters underscores the importance of aquifer recharge that minimizes the influence of evapotranspiration, especially in the west. Unlike other parts of the country where recharge can occur predominantly through infiltration, the high rates of evapotranspiration limit recharge to rapid focused events through exposed karst features within surface-exposed limestone.

Climate Change

Scenarios for climate change in the Edwards Aquifer region indicate that long-term declines in precipitation may occur. For example, projected precipitation differences between

2009 and 2050 based on just a "low greenhouse gas emission" scenario indicate more than seven inches of annual precipitation loss may occur locally in the region (Darby, 2010). Not only is the Edwards Aquifer vulnerable to potential contamination because of its karstic nature, it is among the most vulnerable in the state in relation to changes in climate (Mace and Wade, 2008; Loáiciga et al., 2000). With dryer climate and an anticipated population increase, it is reasonable to expect increased demands on water resources from municipal, agricultural and industrial users. As stated succinctly in the EARIP (2012): "The historical evidence and the results of this research indicate that without proper consideration to variations in Aquifer recharge and sound pumping strategies, the water resources of the Edwards Aquifer could be severely impacted under a warmer climate."

Water Budget

Variations in seasons and climate during the recent history of the Edwards Aquifer are manifested in the variable nature of the aquifer's water budget. Recharge into the system occurs primarily through stream flow networks in the recharge area, which contribute between 60 and 80 percent of the system input (Klemt et al., 1979; Maclay and Land, 1988; Thorkildsen and McElhaney, 1992; Ockerman, 2005), most of which is through open solution channels like fractures and sinkholes (Maclay and Land, 1988). Sharp and Banner (1997) indicate that the remaining 20 to 40 percent of the recharge occurs as direct infiltration within the recharge zone, as well as leakage from the underlying Trinity Aquifer. Leakage from lateral aquifer segments into the San Antonio segment of the Edwards Aquifer and also from adjacent aquifers occurs where hydrologic connections exist, such as along fault zones and through low-confinement border conditions. In Medina County, inflows also occur through recharge structures like surface reservoirs and surface-water diversion to a sinkhole. Based on drainage basin data collected during a period of record from 1934 to 2012, median annual recharge is 556,900 acre-feet[1], with a range from 43,700 acre-feet during the drought of record to 2,486,000 acre-feet in 1992 (EAA, 2013; Figure 1-6). Annual mean and median recharge attributed to structures, from date of construction through 2012, are 853 acre-feet and 4,970 acre-feet, respectively (EARIP, 2012). Recharge estimates of inter-aquifer flow range from 5,000 to more than 100,000 acre-feet per year.

Edwards Aquifer discharge is composed of spring flows and consumptive use through wells (Figure 1-7). Total annual discharge from six of the most significant springs in the region monitored between 1934 and 2012 has varied from 69,800 acre-feet in 1956 to 802,800 acre-feet 1992, with a median annual discharge of 383,900 acre-feet (EAA, 2013). Well discharge estimates during the same period of record range from a low of 101,900 acre-feet in 1934 to a high of 542,400 acre-feet in 1989, with a median annual discharge of 327,800 acre-feet. Total discharge ranged from a low of 388,800 acre-feet in 1955 to a high of 1,130,000 acre-feet in 1992, with a median of 692,900 acre-feet. In 2012, springs comprised 44 percent of total discharge.

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[1] 1 acre-ft = 1,233 m^3

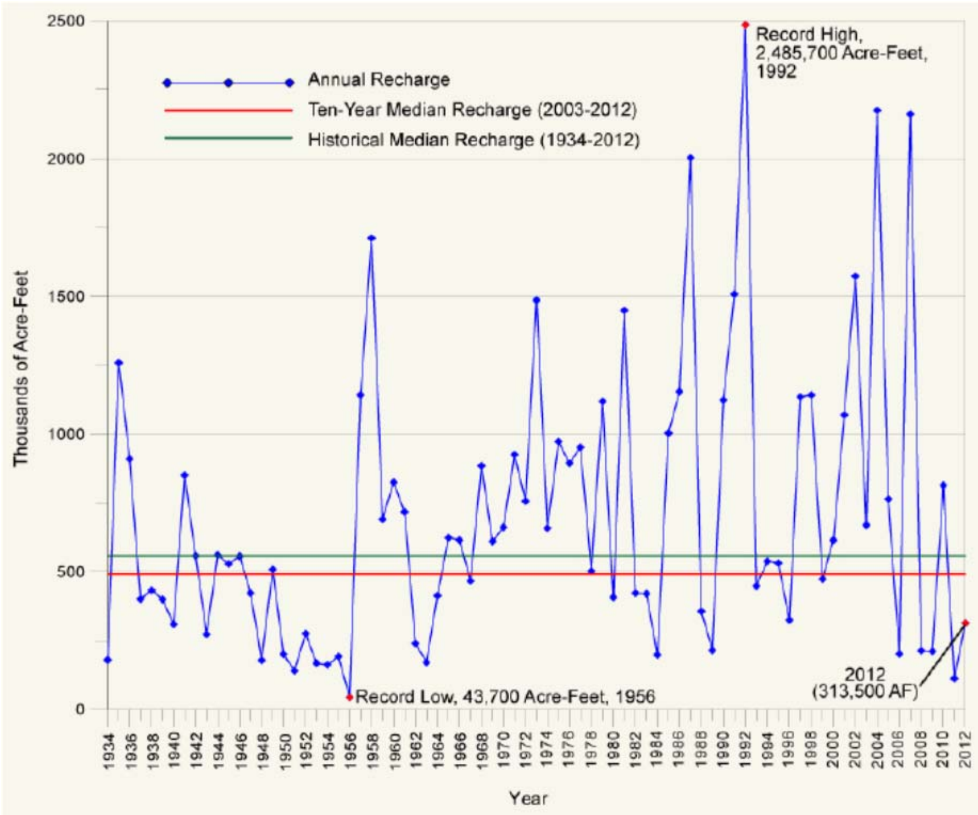

FIGURE 1-6 Estimated Annual Recharge and Ten-Year Floating Median Estimated Recharge for San Antonio Segment of the Edwards Aquifer, 1934 –2012.
SOURCE: Figure 8 from EAA (2013).

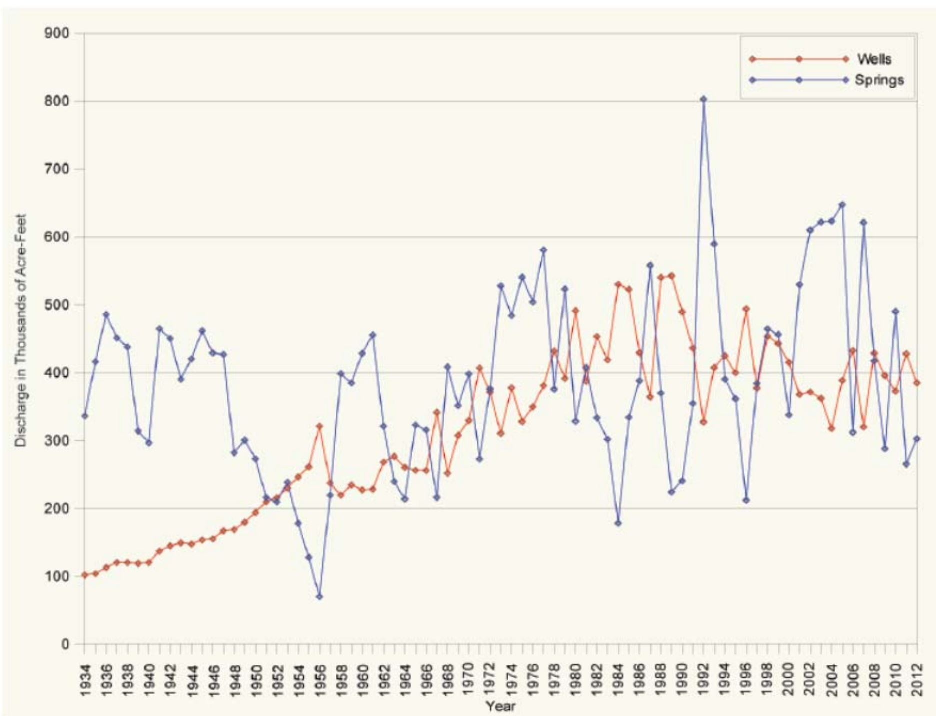

FIGURE 1-7 Groundwater Pumping Compared with Spring Flow from Edwards Aquifer, 1934–2012.
SOURCE: Figure 11 from EAA (2013).

ECOLOGY OF THE EDWARDS AQUIFER REGION

The springs flowing from the Edwards Aquifer and their resulting streams support a number of species, many of which are endemic to the aquifer area. These species include a variety of submersed aquatic vegetation (SAV) like Texas wild rice; several fish, including the fountain darter; amphibians such as the Texas blind salamander; birds like the whooping crane; and a variety of invertebrates. These species' individual habitats range from deep underground in the springs themselves (blind salamander) to the larger streams and lakes (fountain darter and Texas wild rice) within the Edwards system. Some species, like the fountain darter and Texas wild rice, have been well studied, while the ecology of others, like the Comal Springs riffle beetle, is poorly understood. These species are described extensively in later chapters.

The complete Edwards Aquifer-based ecosystem is complex and not yet comprehensively understood. However, to greater or lesser extent, all species in the system depend on spring flow, and reduced flow in Comal and San Marcos Springs has resulted in the intermittent loss of habitat. This loss of habitat from reduced flow is a primary threat to all of these species and the main reason that eight species have been listed, with three more proposed for listing, for protection under the federal ESA (Table 1-1). Spring flow loss is the combined result of naturally fluctuating rainfall patterns, regional pumping of groundwater, and the resulting intermittent drawdown of the Edwards Aquifer. Beyond reduced spring flow, other threats include increased competition and predation from invasive species, direct or indirect habitat destruction or modification by humans (e.g., recreational activities and reservoir construction), and other factors such as high nutrient loading and bank erosion that negatively affect water quality (USFWS, 1996). Invasive species of concern include the Asian trematode *Centrocestus formosanus, a* parasite that attaches to fish's gill filaments, including fountain darters; the giant rams-horn snail, which grazes on aquatic plants and could negatively impact fountain darter habitat during low flow conditions; non-native fish such as tilapia and suckermouth catfish; and non-native plants, three of which—*Hydrilla verticillata*, *Hygrophila polysperma*, and *Colocasia esculenta*—have significantly altered both the Comal and San Marcos ecosystems.

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
Comal Springs Salamander	*Eurycea* sp.	**Petitioned
Texas Troglobitic Water Slater	*Lirceolus smithii*	Petitioned

*Listed as under review by the USFWS
**Listed as undefined status by the USFWS

OVERVIEW OF THE ENDANGERED SPECIES ACT

Congress enacted the current ESA in 1973 to replace several precursor statutes. According to the U.S. Supreme Court in its 1978 decision in *Tennessee Valley Authority v. Hill*, 437 U.S. 153, 174, 184 (1978), "the language, history, and structure of the [ESA] indicates beyond doubt that Congress intended endangered species to be afforded the highest of priorities," and "[t]he plain intent of Congress in enacting this statute was to halt and reverse the trend toward species extinction, whatever the cost."

There are four operative provisions of the ESA that are relevant to the Edwards Aquifer. First, Section 4, 16 U.S.C. § 1533, governs the listing of species and the establishment of their critical habitat. Until either the U.S. Fish & Wildlife Service (FWS) or the National Marine Fisheries Service formally lists a species for protection pursuant to Section 4, that species receives no federal protection. All of the Edwards Aquifer ESA-listed species were listed under the FWS's jurisdiction.

Second, once a species is listed, it is protected from federal agency actions that might affect its continued survival. Under Section 7, 16 U.S.C. § 1536, federal agencies must consult regarding listed species; must use their discretionary authorities to conserve listed species; and cannot engage in, fund, or authorize/license/permit activities that will either jeopardize the continued existence of listed species or damage or destroy a listed species' critical habitat—that is, the designated habitat that the species requires to survive and to recover.

Third, under Section 9, 16 U.S.C. § 1538, endangered species are protected from individual actions that could hurt both members of the species and the species as a whole. Unlike Section7, Section 9 applies to everyone. It prohibits most trade and commerce in endangered species. In addition, and more importantly for the Edwards Aquifer, with respect to endangered species of fish and wildlife, Section 9 prohibits the "take" of such species, which the ESA defines to mean "harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct" (16 U.S.C. § 1532(9)). With regard to endangered species of plants, like Texas wild rice, Section 9 makes it illegal to "remove and reduce to possession any such species from areas under Federal jurisdiction; maliciously damage or destroy any such species on any such area; or remove, cut, dig up, or damage or destroy any such species on any other area in knowing violation of any law or regulation of any State or in the course of any violation of a State criminal trespass law" (16 U.S.C. § 1538(a)(2)(B)). Through a default regulation, threatened species receive all of the same protections that endangered species do *unless* the relevant Service promulgates a special regulation for a specific threatened species.

Fourth, both federal agencies and private entities can receive exemptions from Section 9 "take" liability. For federal agencies, the relevant Service can issue an Incidental Take Statement during a Section 7(a)(2) consultation, authorizing a limited number of incidental "takes" in the course of an activity that the agency is conducting, funding, or permitting. In turn, private individuals and entities and non-federal governments can acquire, pursuant to Section 10, 16 U.S.C. § 1539, a variety of different permits that allow activities that would otherwise violate the Section 9 take prohibition. The most important of these is the Incidental Take Permit [16 U.S.C. § 1539(a)], which is the permit that the EAA sought with respect to the ESA-listed Edwards Aquifer species.

In order to receive an Incidental Take Permit (ITP), the applicant must, *inter alia*, develop a Habitat Conservation Plan (HCP). Thus, it is Section 10 that governs the Edwards Aquifer Authority's ITP and HCP.

THE EDWARDS AQUIFER AUTHORITY AND THE HABITAT CONSERVATION PLAN

The Edwards Aquifer ESA-listed species have been the subject of litigation since at least 1991. For example, one lawsuit, *Sierra Club v. Glickman*, 156 F.3d 606 (5th Cir. 1998), alleged that the U.S. Department of Agriculture was violating Section 7 through its incentives to local agriculture. Another lawsuit, *Sierra Club v. City of San Antonio*, 112 F.3d 789, 791-92 (5th Cir. 1997), alleged that the City's pumping of the aquifer causes Section 9 takes at the springs. Yet another lawsuit, *Shields v. Babbitt*, 229 F. Supp. 2d 638, 646-47 (W.D. Tex. 2000), alleged that other individual groundwater pumpers were causing Section 9 takes of the Edwards aquifer ESA-listed species.

The EAA came into being as a result of *Sierra Club v. Lujan*, No. MO-91-CA-069, 1993 WL 151353 (W.D. Tex. Feb. 1, 1993), which the Sierra Club filed in 1991 against the U.S. Department of the Interior, which houses the FWS. In its 1993 decision resolving this case, the U.S. District Court for the Western District of Texas threatened to effectively federalize management of the Edwards Aquifer unless the State of Texas regulated withdrawals from the aquifer in compliance with the ESA (*Sierra Club* *33-*35). To avoid federal regulation of the aquifer (Bennett, 2012; Miles, 1997), the Texas Legislature enacted the Edwards Aquifer Authority Act in 1993, which the Texas Supreme Court unanimously upheld as facially constitutional in 1996 in *Barshop v. Medina County Underground Water Conservation District*, 925 S.W.2d 618, 623 (Tex. 1996).

The Edwards Aquifer Authority Act created the EAA, which regulates groundwater withdrawals from the Edwards Aquifer. Specifically:

> "The Act imposes an aquifer-wide cap on water withdrawals by non-exempt wells of 450,000 acre-feet of water per year through the year 2007 and 400,000 acre-feet per year thereafter. The Authority can increase the withdrawal caps if it determines that additional water supplies are safely available from the aquifer. The Authority will allocate these caps among wells by a permit system. However, all wells producing no more than 25,000 gallons of water a day for domestic or livestock purposes are exempt from the permit system and the caps. This exemption allows all landowners, except those within or serving a platted subdivision, to drill wells for household purposes, watering animals, or irrigating a family garden."

(*Barshop* 624 n.2). While the permitting program gives preference to existing users of water from the Edwards Aquifer, it also allows the Authority to reduce those established uses (*Barshop* 624 n.2).

Then-existing water users who have either been denied permits or been issued permits to pump reduced amounts of water from the Edwards Aquifer have sued continuously to stop implementation of the Edwards Aquifer Authority Act. These lawsuits include, for example, *Edwards Aquifer Authority v. Bragg*, 21 S.W.3d 375 (Tex. App. 2000); *Bragg v. Edwards*

Aquifer Authority, 71 S.W.3d 729 (Tex. 2002); *Edwards Aquifer Authority v. Peavy Ranch*, 199 S.W.3d 312 (Tex. App. 2006); *Edwards Aquifer Authority v. Chemical Lime, Ltd*., 212 S.W.3d 683 (Tex. App. 2006), *rev'd*, 291 S.W.3d 392 (Tex. 2009); *In re Edwards Aquifer Authority*, 217 S.W.3d 581 (Tex. App. 2006); and *Edwards Aquifer Authority v. Day*, 274 S.W.2d 742 (Tex. App. 2008), *aff'd*, 369 S.W.3d 814 (Tex. 2012). While the Authority has continued since 1996 to issue groundwater permits, the Texas Court of Appeals in August 2013 deemed the Authority's permits limiting historical pumping to be an unconstitutional taking without compensation of landowners' rights to groundwater (*Edwards Aquifer Authority v. Bragg*, No. 04-11-00018-CV, 2013 WL 4535935, Tex. App. Aug. 28, 2013). The court amended its opinion—but not its conclusion—in November 2013 in *Edwards Aquifer Auth. v. Bragg*, No. 04-11-00018-CV, 2013 WL 5989430, at *14–15 (Tex. App. Nov. 13, 2013; "Bragg decision"). If upheld on appeal, this decision has potentially significant financial and legal implications for the viability of the Edwards Aquifer permitting system and hence for the Edwards Aquifer HCP.

The Incidental Take Permit and Habitat Conservation Plan

Despite litigation over the groundwater permitting program, the EAA and several other entities pursued an ESA Section 10 ITP to limit their potential Section 9 liability for permitting the continued pumping and use of Edwards Aquifer water. The ITP application process, as noted, required an HCP. Importantly, given the potential conflict between the ESA's requirements to protect threatened and endangered species endemic to the Edwards Aquifer and its primary springs and the region's reliance on the Edwards Aquifer for its freshwater needs, it took years and the involvement of many parties to craft the approved HCP.

In 2006, FWS issued an invitation to stakeholders in the Edwards Aquifer region to collaborate in a voluntary effort to contribute to the recovery of threatened and endangered species in the Edwards Aquifer region (USFWS, 2012), an initiative that came to be known as the Edwards Aquifer Recovery Implementation Program. In 2007, the Texas Legislature directed 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 to participate in the Edwards Aquifer Recovery Implementation Program and to develop a plan for managing the Edwards Aquifer in a manner that would protect and conserve the federally listed species in the event of conditions similar to the drought of record. In January 2012, the Edwards Aquifer Recovery Implementation Program submitted the Edwards Aquifer HCP to be used in support of an ITP application to the FWS.

FWS granted the ITP on March 18, 2013 (USFWS, 2014). The permit will last 15 years, 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. The ITP allows incidental take for the 11 covered species as detailed in Table 1-2. Importantly, although the HCP supports the FWS's decision to issue the Section 10 Edwards Aquifer ITP, legally it is compliance with the ITP that insulates the EAA and other Permittees from liability under ESA Section 9.

TABLE 1-2 Allowances under the Edwards Aquifer Incidental Take Permit

SPECIES	INCIDENTAL TAKE ALLOWED (over 15 years)
Fountain darter	797,000 in Comal system; 549,129 in San Marcos system
San Marcos Gambusia	Presumed extinct, but otherwise judged by implementation of the HCP.
Comal Springs Dryopid Beetle	1,543
Comal Springs Riffle Beetle	11,179
Peck's Cave Amphipod	18,224
Texas Wild Rice	*Plant; different standards.
Texas Blind Salamander	10
San Marcos Salamander	263,857
Texas Cave Diving Beetle	Judged by minimum flow requirements
Comal Springs Salamander	Judged by minimum flow requirements
Texas Troglobitic Water Slater	Judged by minimum flow requirements

While the subject of monitoring incidental take in the Edwards Aquifer system is not this Committee's main charge, the Committee nevertheless notes that the numerical incidental take allowances in the ITP (Table 1-2) are unrealistically precise. It is not clear that the EAA could meaningfully monitor incidental take, such as from human-induced habitat modification. Nevertheless, total incidental take could become important to other EAA implementation activities because while maintaining the HCP's required minimum flows constitutes compliance with *some* of the ITP's incidental take allowances, that is not true for *all* of them, and the ITP's take limits take priority over HCP implementation (ITP, p. 1, ¶ E).

A timeline of important events in the creation of the HCP for the Edwards Aquifer is shown in Table 1-3.

Species Covered by the HCP

The HCP applies to 11 Edwards Aquifer species—the eight already listed under the federal ESA and three others that have been proposed for listing (Table 1-1). The Permittees considered extending the HCP to an additional 34 species, based on the following criteria: (1) the likelihood that the species would be listed during the permit term; (2) the possible effect of HCP Covered Activities[2] on the species; (3) the status of knowledge about the species (in relation to meeting permit issuance criteria regarding demonstrating the link between the Covered Activities and take); and (4) potential problems with implementation of the HCP regarding requirements by the species. Thirteen of these species are listed in Table 1-4; the HCP did not identify the other 21 species that the applicants considered.

[2] Covered activities refer to four categories of activities that may result in incidental take of endangered fish and wildlife: (1) the regulation and use of the Aquifer; (2) recreational activities in the Comal and San Marcos spring and river ecosystems; (3) other activities in, and related to, the Comal and San Marcos springs and river ecosystems; and (4) activities involved in and related to the implementation of the minimization and mitigation measures in these ecosystems.

TABLE 1-3 Timeline of Important Events for the Edwards Aquifer Habitat Conservation Plan

1950s	Drought of record in Edwards Aquifer region, which now provides the benchmark for the HCP.
June 13, 1956	Comal Springs stops flowing for the first time in recorded history.
1959	Texas legislature forms Edwards Underground Water District in response to the drought.
March 11, 1967	U.S. FWS lists the Texas blind salamander as an endangered species under a precursor statute to the current ESA.
Oct. 13, 1970	U.S. FWS lists the fountain darter as an endangered species under a precursor statute to the current ESA.
1973	Congress enacts the federal Endangered Species Act (ESA).
May 27, 1978	U.S. FWS lists Texas wild rice as an endangered species under the ESA.
July 14, 1980	U.S. FWS lists the San Marcos gambusia as an endangered species and the San Marcos salamander as a threatened species under the ESA.
1984	ESA petition filed to list the Edwards Aquifer diving beetle.
1991	Sierra Club files *Sierra Club v. Lujan*, alleging that the U.S. FWS has failed to protect ESA-listed species in the Edwards Aquifer region.
Feb. 1, 1993	The U.S. District Court for the Western District of Texas decides *Sierra Club v. Lujan*, finding a violation of the ESA and threatening to federalize management of the Edwards Aquifer if the Texas Legislature does not act.
1993	Texas Legislature enacts the Edwards Aquifer Authority (EAA) Act, creating the EAA and a permit system for water withdrawals from the aquifer.
1996	Texas Supreme Court upholds the EAA Act as facially constitutional.
Dec. 18, 1997	U.S. FWS lists the Comal Springs Riffle Beetle, the Comal Springs Dryopid Beetle, and the Peck's Cave amphipod as endangered species under the ESA.
2006	U.S. FWS invites interested parties to discuss approaches to the challenges of aquifer management to balance the region's water needs with those of listed species. This leads to the Edwards Aquifer Recovery implementation program.
2012	Texas Supreme Court decides *Edwards Aquifer Authority v. Day*, concluding that landowners along the Edwards Aquifer have a property right to the aquifer's groundwater *in situ*.
Aug. 2012	U.S. FWS formally proposed to list the Jollyville Plateau salamander, Austin blind salamander, Georgetown salamander, and Salado salamander as endangered.
Feb. 15, 2013	U.S. FWS approves the Edwards Aquifer Incidental Take Permit and its HCP
March 18, 2013	Edwards Aquifer ITP and HCP take effect. Phase I begins.
Aug. 2013	Texas Court of Appeals decides *Edwards Aquifer Authority v. Bragg*, concluding that the implementation of the Edwards Aquifer permit program effectuated a constitutional “taking” of landowners' property rights in groundwater.
Jan. 2014	Natural Research Council Committee to Review the Edwards Aquifer Habitat Conservation Plan is constituted.
March 2020	Phase I of the HCP scheduled to end. Phase II, utilizing adaptive management, scheduled to begin.
March 31, 2028	The current Edwards Aquifer ITP and HCP will expire.

TABLE 1-4 Common and Scientific Names and ESA Status of Species Considered But Not Proposed For Coverage in the Edwards Aquifer HCP.

Common Name	Scientific Name	ESA Status
Mimic Cavesnail	*Phreatodrobia imitate*	Under review
Blanco Blind Salamander	*Eurycea robusta*	*Not listed
Comal Blind Salamander	*Eurycea tridentifera*	Under review
Texas Salamander	*Eurycea neotenes*	Under review
Toothless Blindcat	*Trogloglanis pattersoni*	Under review
Widemouth Blindcat	*Satan eurystomus*	Under review
Whooping Crane	*Grus americana*	Endangered
Texas Fatmucket	*Lamspilis bracteata*	Candidate
Golden Orb	*Quadrula aurea*	Candidate
Texas Pimpleback	*Quadrula petrina*	Candidate
False Spike Mussel	*Quincuncina mitchelli*	Under review
Salina Mucket	*Disconaias salinasensis*	**Not listed
Mexican Fawnsfoot	*Truncilla cognata*	Under review

*Threatened status as determined by the Texas Parks and Wildlife Department
**Endangered status as determined by the International Union for Conservation of Nature

Species were eliminated for coverage for a variety of reasons. For example, the Permittees decided not to have the HCP cover the Mimic Cavesnail, the salamander *Eurycea robusta*, and two catfishes because they exist only in the deeper portions of the Aquifer. The Permittees concluded that the HCP activities, which would affect only the "top" of the aquifer, would not directly affect these species. The Permittees excluded the six mussel species in Table 1-4 because these species do not occur in the headwaters of the Comal and San Marcos Springs. Similarly, the two salamanders *Eurycea tridentifera* and *Eurycea neotenes* do not occur in Comal or San Marcos Springs. The Whooping Crane, which overwinters far downstream in the river system near Aransas National Wildlife Refuge, was not included for coverage under the HCP because the Permittees believed that: (1) factors affecting the crane and its habitat are not under the control of the EAA and its partners and (2) Whooping Cranes would not be affected adversely by the Covered Activities (EARIP, 2012). This issue is revisited in the final chapter of this report.

The Role of Indicator Species under the HCP

Rather than attempting to devise an HCP that would address all 11 Covered Species individually, the HCP identifies three indicator species—the fountain darter, the Comal Springs riffle beetle, and Texas wild rice—to represent all Covered Species. The HCP assumes that all of its habitat minimization and mitigation measures for these three species will be sufficient to protect all Covered Species (EARIP, 2012). In addition, the use of indicator species potentially reduces the cost of implementing activities to minimize species impacts and of implementing mitigation measures, as well as the costs and time-consuming efforts associated with processing individual incidental take permits (USFWS, 2013).

The **fountain darter** (*Etheostoma fonticola*) is a subtropical, benthic freshwater fish of the family *Percidae* that was federally listed as an endangered species in 1970 (USFWS, 1970). First documented and described in 1886 by Jordan and Gilbert, fountain darters are found only in

the San Marcos and Comal Springs and their effluent rivers (Guadalupe River system) in southern central Texas (Page and Burr, 1991). Fountain darters are small (maximum total length of about 4.3 cm) and inhabit clear, clean, flowing, and thermally constant waters with undisturbed sand and gravel substrates, rock outcrops, and areas of submerged vegetation (algae, moss, vascular plants) for cover (EARIP, 2012). They generally eat small aquatic invertebrates, such as copepods, aquatic insect larvae, and amphipods (EARIP, 2012).

The **Comal Springs riffle beetle** (*Heterelmis comalensis*) is a small (~0.2 cm), flightless member of the Elmidae, native to the headwaters of the Comal and San Marcos Rivers (Bosse et al., 1988). It was listed under the ESA as an endangered species in 1997, along with two other co-occurring invertebrates, the Comal Springs dryopid beetle *(Stygoparnus comalensis*) and Peck's Cave amphipod (USFWS, 1997). Both immature and adult Comal Springs riffle beetles are aquatic. The adults are known to feed primarily on algae and detritus scraped from submerged weeds and rocks (EARIP, 2012), and larval food resources are likely to be similar but have not been documented. Comal Springs riffle beetles are found in flowing waters of the spring runs, as well as in spring flow areas along the Landa Lake shoreline and in spring flow upwelling areas in the lake (BIO-WEST, 2002). In 2007, the USFWS designated 19.8 acres of the Comal Springs complex and 10.5 acres of the San Marcos Springs complex as critical habitat for Comal Springs riffle beetles, dryopid beetles and Peck's Cave amphipod (USFWS, 2007).

Texas wild rice (*Zizania texana*) is an aquatic perennial grass from the family *Poaceae*. It was originally collected in 1892, described in 1932 as southern wild rice (*Z. aquatica*), recognized as a new species in 1933 by W. A. Silveus, and re-described by A. C. Hitchcock in 1933 (EARIP, 2012). Texas wild rice is an aquatic, monoecious, perennial macrophyte. It is found growing and submerged primarily at a depth of one meter or less in swift moving, shallow areas of the San Marcos River. Flowering typically occurs in the spring and fall but may be seen throughout the year because of the constant water temperatures in the Edwards Aquifer system. Texas wild rice also reproduces vegetatively by stolons and appears to reestablish readily when uprooted and relocated during flood events (EARIP, 2012).

Other Covered Species

The **Comal Springs dryopid beetle** (*Stygoparnus comalensis*) is subterranean species inhabiting the Comal Springs system that was listed as endangered in 1997 (USFWS, 1997). Comal Springs dryopid beetles are small (~3mm), slender, reddish-brown beetles. Comal Springs dryopid beetles are restricted to the headwaters of the springs and spring upwelling areas (EARIP, 2012).

Peck's cave amphipod (*Stygobromus pecki*), also a subterranean species found in the Comal and Hueco Springs, 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 (USFWS, 1997). Like all members of the genus *Stygobromus*, Peck's cave amphipods are eyeless, unpigmented and approximately 3 mm long. Like the Comal Springs dryopid beetle, the Peck's cave amphipod appears to be restricted to the headwaters of the springs and spring upwelling areas (EARIP, 2012).

The **San Marcos salamander** (*Eurycea nana*) is a member of the plethodontid lungless salamanders (Bishop, 1943). San Marcos Salamanders are known only from a pool at the source

of the San Marcos River (San Marcos Springs, Spring Lake) and a short distance downstream (Chippindale et al., 2000) and have been listed as threatened since 1980. San Marcos salamanders are small (maximum length of about 58 mm), slender, and light brown in color. They are found in Spring Lake in rocky areas around spring openings and downstream of the dam at Spring Lake (Tupa and Davis, 1976; Nelson, 1993).

The **Texas blind salamander** (*Eurycea rathbuni*) is a smooth, unpigmented subterranean species found only in San Marcos Spring (Longley, 1978). It has a maximum length of about120 mm, a large and broad head, reduced eyes (two small dark spots beneath the skin), long and slender limbs, four toes on the forelegs and five on the hind legs. As evidenced by the presence of juveniles year round, the Texas blind salamander appears to be sexually active throughout the year because of the thermally constant waters of the Edwards Aquifer (EARIP, 2012).

The **Edwards Aquifer Diving Beetle** (*Haideoporus texanus*), **Comal Springs Salamander** (*Eurycea sp.*), and **Texas Troglobitic Water Slater** (*Lirceolus smithii*) are not presently listed under the federal ESA, but petitions to list them have been filed with the FWS. The Edwards Aquifer diving beetle, also known as the Texas cave diving beetle, is a small (typically less than 13 mm), 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). Little is known of the Comal Springs salamander, which exists as a single population in the Comal Springs and has been subject of systematic debate since the 1970s. The Texas Troglobitic Water Slater is a small, blind, non-pigmented 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).

Covered Activities under the HCP

As ESA Section 10 requires, the Edwards Aquifer HCP specifies the steps that the EAA and other Permittees will take to minimize and mitigate the incidental take of ESA-listed species associated with the Covered Activities (e.g., permitted water withdrawals for drinking water supply, agriculture, and other purposes, and recreation). The Permittees will implement the HCP in two phases (Phase I is the first seven years, followed by Phase II for the remainder of the permit). During the first phase, they will put in place habitat minimization and mitigation measures to maintain continuous minimum spring flow during a repeat of the drought of record. The minimization and mitigation measures fall roughly into two categories (see Box 1-1).

First, there are four spring flow protection measures designed to provide additional water during drought periods. These include critical period management, regional water conservation, a voluntary irrigation suspension program, and aquifer storage and recovery. Critical period management refers to reductions in permitted discharges when the spring flow at Comal Springs and well levels at J-17 fall below certain levels. The HCP instituted a new stage, Stage V, which would mandate reductions in pumping of 44 percent. The second measure 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 acre-feet/year. The third item, the voluntary irrigation suspension program (VISPO), targets the 30 percent of annual

Edwards Aquifer pumping that is withdrawn for irrigation. VISPO relies on permitted irrigators relinquishing their pumping rights when well levels and spring flows drop below certain triggers; it is intended to conserve another 40,000 acre-feet/yr. Finally, the San Antonio Water System (SAWS) runs an aquifer storage and recovery (ASR) operation in the Carrizo Aquifer that will be expanded and is predicted to make the greatest contribution to overall Edwards Aquifer water savings (as much as 100,000 acre-feet/year).

As the largest retail water agency that pumps water from the Edwards Aquifer, SAWS has taken steps to develop additional supplies that are not dependent upon the Edwards Aquifer and are separate from the HCP. By developing these supplies, SAWS reduces San Antonio's reliance on the Edwards Aquifer, particularly during times of drought. Additional water supplies being developed by SAWS include brackish groundwater from the Wilcox Aquifer, recycled water, and the Vista Ridge Pipeline (http://www.saws.org/Your_Water/WaterResources/projects/; accessed 10-27-2014). SAWS is developing a desalination facility to produce 13,400 acre-feet/year from brackish groundwater in the Wilcox Aquifer in southern Bexar County. The desalination facility could be expanded in future phases to produce up to 33,600 acre-feet/year. SAWS has developed a recycled water system capable of providing up to 25,000 acre-feet/year. Recycled water is supplied for irrigation and industrial uses, and to supplement flows in the San Antonio River and Salado Creek. SAWS approved the Vista Ridge Pipeline Project in October 2014, and it is projected to provide water to San Antonio by year 2020. The project includes 142 miles of pipeline to provide San Antonio up to 50,000 acre-feet/year of groundwater pumped from the Carrizo Aquifer in Burleson County.

Second, beyond spring flow protection measures there are a variety of minimization and mitigation measures designed to maintain and restore the habitat of ESA-listed species at both Comal and San Marcos Springs (see Box 1-1). These measures include such activities as riparian zone restoration, removal of invasive plant species, replanting of native species, management of recreational activity, pollution prevention, and public education.

Box 1-1

Minimization and Mitigation Measures in the Habitat Conservation Plan
Modified from EARIP, 2012

Numbers in parentheses indicate the HCP Section where the activity is described.
Note that all 38 activities are line items in the HCP budget.

Flow Protection Measures

1. Critical Period Management Stage V (5.1.4)
2. Use of SAWS Aquifer Storage and Recovery (ASR) for spring flow protection trade off (5.5.1)
3. Regional Water Conservation Program (5.1.3)
4. Voluntary Irrigation Suspension Program Option (5.1.2)

M&M measures specific to San Marcos Springs

5. Texas wild rice enhancement and restoration (5.3.1 and 5.4.1)
6. Sediment removal in Sewell Park (5.3.6 and 5.4.4)

continued

Box 1-1 Continued

7. Aquatic vegetation restoration (non-native removal, native reestablishment) (5.3.8, 5.4.3, 5.4.12)
8. Management of floating vegetation mats and litter removal (5.3.3 and 5.4.3)
9. Non-native animal species control (5.3.5. 5.3.9, 5.4.11, 5.4.13)
10. Sessom Creek sand bar removal (5.4.6)
11. Low impact development/BMPs (5.7.3)
12. Recreation control in key areas (5.3.2, 5.4.2)
13. Restoration of riparian zone with native vegetation (5.7.1)
14. Bank stabilization/permanent access points (5.3.7)
15. Biomonitoring (6.3.1)
16. Water quality monitoring and protection (5.7.2, 5.7.6)
17. Household hazardous waste program (5.7.5)
18. Other measures
    a. Management of public recreational use (5.3.2.1)
    b. Prohibition of hazardous materials route (5.3.4)
    c. Diversion of surface water (5.4.5)
    d. Diving classes in Spring Lake (5.4.7)
    e. Creation of scientific areas (5.6)
    f. Research programs in Spring Lake (5.4.8)
    g. Boating in Spring Lake and Sewell Park (5.3.10)
    h. Septic system registration and permitting program (5.7.3)
    i. Management of golf course grounds (5.4.9)

M&M measures specific to Comal Springs

19. Old Channel Environmental Restoration and Protection Area (ERPA) (5.2.2.1)
20. Flow-split management (5.2.1)
21. Landa Lake and Comal River aquatic vegetation restoration/maintenance (5.2.2 except 5.2.2.1)
22. Non-native animal species control (5.2.5, 5.2.9)
23. Decaying vegetation removal program (5.2.4)
24. Riparian improvements and sediment removal specific to the Comal Springs Riffle Beetle (5.2.8)
25. Gill parasite control and non-native snail removal program including optimization research (5.2.6)
26. Restoration of riparian zone with native vegetation (5.7.1)
27. Prohibition of hazardous materials route (5.2.7)
28. BMPs for stormwater control (5.7.6)
29. Incentive program for Low Impact Development (LID) (5.7.6)
30. Biomonitoring (6.3.1)
31. Water quality monitoring (5.7.4)
32. Household hazardous waste program (5.7.5)
33. Other measures
    a. Creation of state scientific areas (5.6)
    b. Management of public recreational use (5.2.3)

Measures for both systems

34. Development of a mechanistic ecological model (6.6.3)
35. Applied environmental research at the FWS National Fish Hatchery and Training Center (6.3.4)
36. Science Review Panel
37. Improve Groundwater Model
38. National Fish Hatchery and Training Center Refugia (5.1.1)

Phase II of the HCP term adds the possibility of adaptive management. More specifically, the Permittees will continue to implement all of the Phase I measures throughout the 15-year permit term unless information developed during Phase I indicates that they should implement additional or alternate measures during Phase II as part of a formal adaptive management process (EARIP, 2012). The Permittees expect that some of the initial minimization and mitigation measures will require modification after seven years because of the current uncertainty associated with both their hydrological and ecological models and to incorporate knowledge gained during Phase I.

Several of the minimization and mitigation measures found in Box 1-1 are specifically intended to provide information that will feed into the formal Adaptive Management Process separating Phase I from Phase II. In particular, the EAA is conducting extensive water quality and biological monitoring of the aquifer and spring systems to gather baseline information, document trends, and eventually determine whether HCP minimization and mitigation measures are leading to species recovery. Biological monitoring of the Comal and San Marcos Spring systems has been in place since 2000 and focuses on the full suite of ESA-listed species as well as SAV. Water quality monitoring began much earlier and encompasses the aquifer, the springs, sediments, and the river systems downstream.

A second major activity that the EAA expects will provide the basis for adaptive management is improving the groundwater hydrologic model for the Edwards Aquifer. Two parallel efforts are ongoing: (1) updating the existing USGS MODFLOW model of the aquifer, which uses a finite difference code, and (2) creating a new finite element model of the aquifer. According to the HCP, the creation of two models, both of which can be adapted for karst terrain, is expected to help quantify the uncertainty associated with groundwater modeling. Along with model development, the EAA has also undertaken the refinement of the conceptual model of the Edwards Aquifer, including a better understanding of recharge and discharge.

A third major activity specified in the HCP is the creation of predictive ecological models for Comal and San Marcos Springs. Although the HCP does not say specifically what models should be pursued for what organisms, the EAA's initial efforts are focusing on mechanistic models for fountain darter, SAV (which is prime fountain darter habitat and could eventually be useful for modeling Texas wild rice), and Comal Springs riffle beetle. These efforts are meant to build upon the HCP's Habitat Suitability analyses, which led to the current minimum recommended spring flows at Comal and San Marcos Springs to maintain viable populations of the ESA-listed species. A major goal of the ecological modeling is to more accurately establish threshold levels for these taxa and associated species relative to potential environmental stressors, such as a reduction in spring flow. Another goal of the ecological modeling is to be able to predict the long-term effects of the Covered Activities on these species.

Finally, the HCP created an Applied Research Program to fund individual research projects to study the ecological dynamics within the Comal and San Marcos Spring systems. The goals of these year-long projects are to inform the ecological modeling program and also to fill gaps in knowledge about the various species. Given the EAA's Aquifer Science Research Program and the more advanced state of hydrologic modeling, the Applied Research Program has focused exclusively on ecological topics.

The budget for the HCP varies between $15-20 million per year over its 15-year tenure (see Chapter 7 of EARIP, 2012).

THE EAA REQUESTED STUDY

In late 2013, the EAA formally requested the involvement of the National Research Council to provide advice on the many different scientific initiatives underway to support the HCP. An expert committee of the NRC 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 minimization and mitigation measures to use and their effectiveness, and (3) make decisions about the transition from Phase I to Phase II of the HCP. The NRC will conduct its study from 2014 to 2018 and produce three reports. Box 1-2 gives the Statement of Task for this first report.

As Box 1-2 indicates, this report focuses on improving modeling efforts for the Edwards Aquifer. Subsequent NRC reports will review the performance of minimization and mitigation measures, including the four spring flow protection measures, as well as the adequacy of the biological goals and objectives to protect the endangered species.

Box 1-2

Review of the Edwards Aquifer Habitat Conservation Program—Phase 1
Statement of Task

A committee of the National Research Council will review and provide advice on four scientific initiatives within the Edwards Aquifer Habitat Conservation Program: (1) ecological modeling, (2) hydrologic modeling, (3) biological and water quality monitoring programs, and (4) applied research. The committee's report will address:

- hydrological and ecological modeling approaches,
- accuracy and reliability of the assumptions used to support development of both conceptual and quantitative models,
- adequacy of data for model calibration and verification,
- identification and description of uncertainties,
- additional monitoring data needs,
- additional research needs, and
- other issues deemed relevant by the committee.

In addition, the committee will assess the sufficiency of the modeling, research, and monitoring under development to support the EAHCP Phase II strategic decisions and questions regarding relationships among conservation measures, biological objectives, and biological goals.

Report Roadmap

Chapter 2 of this report addresses the hydrologic modeling being conducted by the EAA and their contractors. It reviews both the updates to the MODFLOW model and the creation of the finite element model, and it discusses changes to the conceptual model of the aquifer and improvements to estimating recharge—two issues that could impact both models. The chapter ends with a consideration of uncertainty in groundwater modeling and the identification of

knowledge gaps. This and all subsequent chapters reflect consideration of EAA reports through November 2014.

Chapter 3 describes the state of ecological modeling for Comal and San Marcos Springs, focusing on the initial modeling efforts for fountain darter, SAV, Texas wild rice, and Comal Springs riffle beetle. It reviews the HCP's Habitat Suitability analyses, which have led to the creation of minimum spring flow requirements in the HCP to maintain the ESA-listed species. It then turns to the development of the new ecological models for fountain darter and SAV.

Chapter 4 delves more deeply into both the comprehensive water quality monitoring program and biomonitoring program. It considers the adequacy of the biomonitoring program to provide the necessary data and information for the mechanistic ecological models and makes recommendations for what should continue to be sampled as the HCP moves forward.

Chapter 5 critiques the Applied Research Program, which is populated with short-term research projects that are intended to either inform the ecological modeling or fill critical information gaps.

The final chapter tackles overarching issues, such as the need for data management within the HCP, the benefits of taking a more holistic ecosystems approach, and planning for worst-case scenarios.

It should be noted that 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.

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2

Hydrologic Modeling

This chapter reviews the hydrologic modeling used to support the Edwards Aquifer Habitat Conservation Plan. There are two primary objectives for these modeling efforts. The first objective is to create a model that can reproduce known spring flows, since habitat protection is dependent in part on adequate spring flow. Second, once a model has been developed that meets criteria for suitability, it can be used as a predictive tool. There are two types of predictions needed to support the EAHCP: (1) predicting the effects of future hydrologic conditions (such as climate change and droughts) on spring flow, and (2) predicting how management actions (like conservation measures) will affect water levels and spring flows. This chapter discusses the appropriateness of the hydrologic modeling strategies used for the Edwards Aquifer and it suggests additional analysis to quantify and, if possible, reduce uncertainty and improve defensibility.

INTRODUCTION

Often information necessary for planning, operations, and design of water resources systems are either inadequate or unavailable at locations of interest. It is generally not feasible or cost-effective to perform field experiments to determine the response of the water resources systems to a range of proposed management actions. Thus, practitioners have turned to modeling as a way of predicting the future behavior of an existing or an altered hydrologic system (Loucks, 1990). Groundwater modeling in particular has become an important tool for planning and decision making associated with groundwater management, which entails the efficient utilization of groundwater resources in response to current and future demands while protecting the integrity of the resource to sustain environmental needs (EPA, 1988).

Hydrologic simulation models entail the mathematical description of the components and the response of the hydrologic system to a series of events during a desired time period. All models are simplified representations of the system being modeled. The extent to which system complexity is incorporated depends on the skill of the modeler, the time and money available, and perhaps most importantly the modeler's understanding of the real system (Loucks, 1990).

Modeling typically proceeds in phases. First a conceptual model is developed that, for a fractured rock system like the Edwards Aquifer, should include (a) identification of the most important boundary conditions and features of heterogeneity in the system; (b) identification and orientation of the most important conduit flow paths and fractures in the rock mass (which may indicate anisotropy); and (c) determination of how much water such features conduct. The conceptual model along with field observations and measurements are essential to selecting the

best code for the model, which is the second major phase. The code should meet the requirements of the problem and should be verified to test that the code is functioning properly. Verification involves comparison of the model output to a known (analytical) solution; it is needed to ensure that the code performs as expected with minimal errors. Third, once data are collected for input into the model, model runs can be performed and the results should be compared to measured data, a phase called calibration. During calibration, the modeler selects parameters to adjust and determines the range of parameter values to test. Fourth, once a satisfactory calibration is achieved, the model should be run without adjusting the calibration parameters, and the output should be compared with a new data set not used during the calibration—a phase called validation.

The Committee recognizes the controversy over validating groundwater models of complex systems (see Konikow and Bredehoeft, 1992; Anderson and Woessner, 1992), much of which stems from the inherent difficulty of the task as well as from the inconsistent or unclear use of the term "validation." To help alleviate some of the confusion, Beven and Young (2013) have recommended the term "conditional validation," which implies that the conditions under which the model is being validated are made explicit and they may change in the future. According to these authors, models that have been conditionally validated "have immediate practical utility in simulating within the range of the calibration and evaluation data, while allowing for their updating in the light of future research and development." This report uses the term "validation" to refer to testing of the model's predictive abilities against data that were not used during the calibration phase. Such testing is just one of many procedures that can be used to improve confidence in the model output, as discussed in the section on uncertainty analysis.

It should be noted that the EAA has sometimes used the term "verification" in several of their reports and presentations to the committee when describing model runs that started with existing parameters but allowed for changing parameters to update the model. This is not a typical use of the term verification, nor does it describe the process of validation, and it may confuse those who intend to use the models. Instead, these efforts are more accurately described as additional calibration runs. This distinction becomes important later in the chapter as we review the updates made to the MODFLOW model of the Edwards Aquifer.

GROUNDWATER FLOW MODELS OF THE EDWARDS AQUIFER

Modeling of flow and transport in systems with conduit flow such as the Edwards Aquifer requires the use of complex models designed for the unique hydrogeology characterized by significant heterogeneity in both porosity and permeability (see Box 2-1). The modeling of any system requires the development of, and revisions to, a conceptual model that constitutes a hypothesis describing the main features of geology, hydrological setting, and site-specific relationships between geological structure and patterns of fluid flow.

Over the years, there have been several efforts to characterize the hydrostatigraphy of the Edwards Aquifer with a goal of developing a conceptual model (Maclay, 1995; Lindgren et al., 2004; Worthington, 2004; Hovorka et al., 2004). Lindgren and others (2004) offer a comprehensive literature review of hydrogeology, hydrogeochemistry and karst evolution of the Edwards Aquifer, including characterization of flow; spatial distributions of hydraulic conductivity, storage, and porosity; and delineation of aquifer boundaries. Multiple data

sources were used to develop the 3D framework and characterize 3D properties of the Edwards Aquifer (e.g., Collins, 2000; Small et al., 1996; Hovorka et al., 1995; Mace, 2000), including surface geologic mapping, log analysis, aquifer testing and structural interpretations.

BOX 2-1
Challenges of Modeling the Complex Hydrogeology in the Edwards Aquifer

The hydrostatigraphy of the Edwards Aquifer is extremely complex primarily due to the presence of the Balcones Fault Zone and karst system where soluble host rocks have dissolved preferentially to form large interconnected conduits (see Figure 2-1). A "conduit" is defined as a karst-aquifer feature that is similar to a pipe (>1 ft diameter) through which groundwater flows much more quickly than in the smaller pores and fractures of the surrounding rock. Conduits form by the dissolution of soluble rocks, such as limestone. A "conduit zone" is defined as set of parallel conduits in a group that together perform the same function as one larger conduit. Some models simulate conduits as pipe-flow features, where equations for fluid flow in pipes are used, as opposed to Darcian flow in a uniform porous matrix.

A fault is a fracture or fracture zone along which there has been displacement of two blocks of the earth's crust or a geological formation. The effect of the fault zone on groundwater flow can be diverse; some faults enhance groundwater flow along the fault plane (and hence are preferential pathways), whereas others impede the flow of groundwater crossing the fault (and therefore are called barrier faults).

The extensive fault network in the Edwards Aquifer presents a modeling challenge. While numerous hydrologic studies involving conduit mapping and dye tracing have characterized the system, the nature and extent of spatial porosity and other properties is broadly interpreted in some areas. Hovorka et al. (2004) and Worthington (2004), for example, interpret potentiometric troughs to hypothesize a regional conduit flow system. Lindgren et al. (2004) also note "If flow feeding Comal Springs is dominated by a few large conduits, the few available aquifer tests do not characterize those conduits." Further, Longley (1981) reports blind catfish in a well at 1500 ft below land surface approximately 15 miles away from the recharge zone, suggesting rapid transport through large conduits.

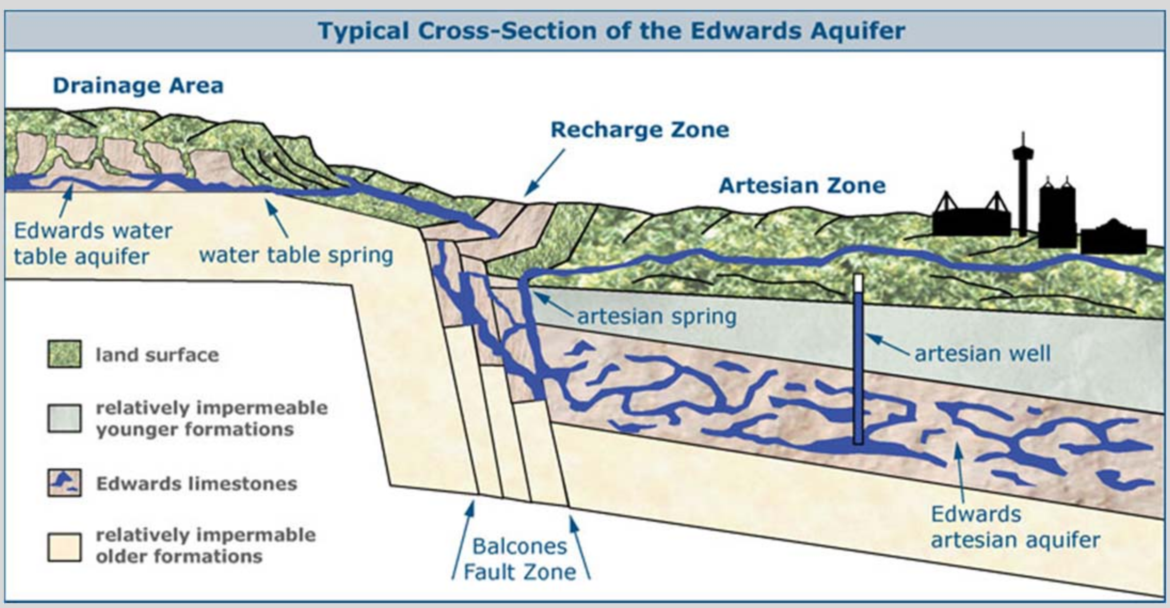

FIGURE 2-1 A simplified representation of a typical cross-section of the Edwards Aquifer.
SOURCE: http://www.edwardsaquifer.net/intro.html

continued

BOX 2-1 Continued

A variety of classification systems exists for mathematical models of fractured aquifers with conduit flow (NRC, 1996; Schmelling and Ross, 2004; Cook, 2003; Bordas, 2005). They generally fall into one of two broad classes: (a) equivalent continuum models; and (b) discrete feature models (see Figure 2-2). In case of the equivalent continuum models, the heterogeneity in the fractured system is simulated using a limited number of regions, each approximated to be an equivalent porous medium (EPM) assuming uniform properties. Discrete network models, commonly known as discrete fracture network (DFN), characterize these features explicitly using such properties as aperture, orientation and length. The main motivation for DFN models is that, at every scale, flow is dominated by a limited number of discrete pathways formed by fractures or conduits (Dershowitz et al., 2004). The extensive data required for DFN models limit their use to sites with a relatively small number of well-defined structures (EPA, 1989). In many cases, the features controlling flow are not known at the scales necessary for modeling. In such instances the stochastic modeling approach in which the physical parameters are described as a random field characterized by a probability distribution may be used (Cook, 2003).

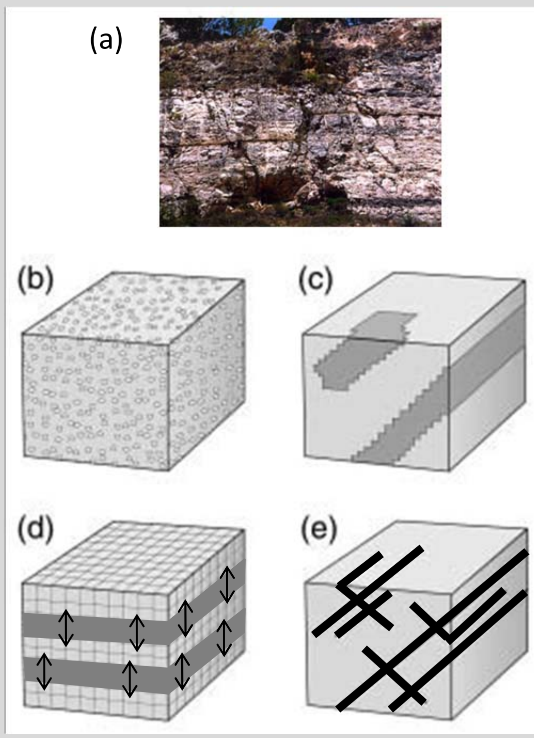

FIGURE 2-2 Different modeling approaches for fractured rock aquifers. These approaches are analogous in karst, and the figure has been modified to show karst approaches. (a) Photograph of an actual karst network; (b) Equivalent porous media model, using uniform aquifer parameters; (c) Equivalent porous media model in which highly fractured zones such as shown in (e) are represented by regions of higher hydraulic conductivity; (d) Dual continuum model in which the matrix and hypothetical high permeability layer or boundary interact through an exchange term (arrows); (e) Discrete fracture or pipe model, in which the major conduits are explicitly modeled; for karst, these discrete features would be pipe-like.
SOURCE: Adapted from Cook (2003).

Most models of the Edwards aquifer are based on the popular MODFLOW code (McDonald and Harbaugh, 1988; and subsequent versions such as Niswonger et al., 2011), developed by the U.S. Geological Survey (USGS). MODFLOW provides estimates of water levels and fluxes (such as spring flow) given inputs that include hydraulic conductivity, recharge, and pumping. It can be used for 2D or 3D flow and under transient conditions (e.g., to evaluate changes in recharge or pumping over time). Most of the Edwards Aquifer models developed so far have used an equivalent porous media (EPM) approach in which aquifer regions are assumed to have uniform aquifer parameters, rather than incorporating karst features. Table 2-1 lists the various numerical models of the Edwards Aquifer, noting how they dealt with karst features. Lindgren et al. (2004) modeled conduits using high permeability zones. Painter et al. (2007) along with Sun et al. (2005) used a version of MODFLOW with a conduit package.

TABLE 2-1 Numerical Groundwater Flow Models of the Edwards Aquifer

Model Code	Geographical extent	Authors	Comments about model structure and conduits
GWSIM	San Antonio segment	Klemt et al. (1979)	EPM
GWSIM	San Antonio segment	Thorkildsen and McElhaney, 1992	Revision of Klemt et al. (1979) EPM
MODFLOW	Barton Springs segment	Scanlon et al. (2002)	EPM
MODFLOW	San Antonio and Barton Spring segments	Lindgren et al. (2004)	Incorporated lines of EPM cells with high K for conduits
MODFLOW	Barton Springs segment	Smith and Hunt (2004)	Revision of Scanlon et al. (2002) EPM
MODFLOW	San Antonio and Barton Spring segments	Lindgren (2006)	Revision of Lindgren et al. (2004) with wide zones of EPM cells for conduits
MODFLOW-DCM	Barton Springs segment	Painter et al. (2007); Sun et al. (2005)	Dual conductivity model (dual porosity type)
EAA 2014 MODFLOW	San Antonio segment	Winterlee 2014a	Revision of Lindgren et al. (2004) that includes zones of cells with high K for conduits in limited areas
TRANSIN	Edwards aquifer	SWRI (ongoing)	Finite-element model using the EPM approach
FEFLOW	Edwards	SWRI (ongoing)	EPM (as of May 2014)

EPM, equivalent porous media; K, hydraulic conductivity

Improvements in model design to facilitate the implementation of the Habitat Conservation Plan (HCP) have led to the last three modeling efforts listed in Table 2-1. The improvements include simulated transient water levels, better aquifer characterization and boundary conditions, new methods for determining recharge and water budgets, and more accurate calibration to springs. The first major modeling activity is that the EAA has added calibration data to develop a 2014 version of the MODFLOW model and used it to test management strategies that are major components of the HCP (discussed further below).

Second, the HCP requires a new model of the Edwards Aquifer to be developed and ready for use by December 31, 2014, and expects it to be a finite element (FE) model. To satisfy the second requirement, the EAA contracted with the Southwest Research Institute (SWRI) to develop a new FE groundwater model of the Edwards Aquifer over a three-year period. The Scope of Work for the FE modeling specified certain requirements including improvements to the conceptual design, boundary conditions, structure of the model (e.g., inclusion of conduits in the groundwater system), and model performances including calibration targets. The model development effort also included a Groundwater Model Review Panel (GMRP) to provide technical assistance and oversight.

EAA’S 2014 MODFLOW Model

The EAA’s 2014 MODFLOW model is a single layer transient flow model to simulate heads and spring flows (HDR, 2011; EAA presentations to the NRC Committee). This version extends from Las Moras Springs near Bracketville in the west to San Marcos Springs in the east. Some versions of the model (Table 2-1) extend east to Barton Springs, but a groundwater divide has been identified between San Marcos and Barton Springs, such that Barton Springs can be considered to be in a separate groundwater basin. The model is bounded on the north by the extent of the Edwards Aquifer outcrop and on the south by the saline zone. Thus, the model area includes the confined and unconfined Edwards Aquifer, but not the contributing area where recharge may enter the Trinity Aquifer and cross over to the Edwards Aquifer (see Figure 2-3).

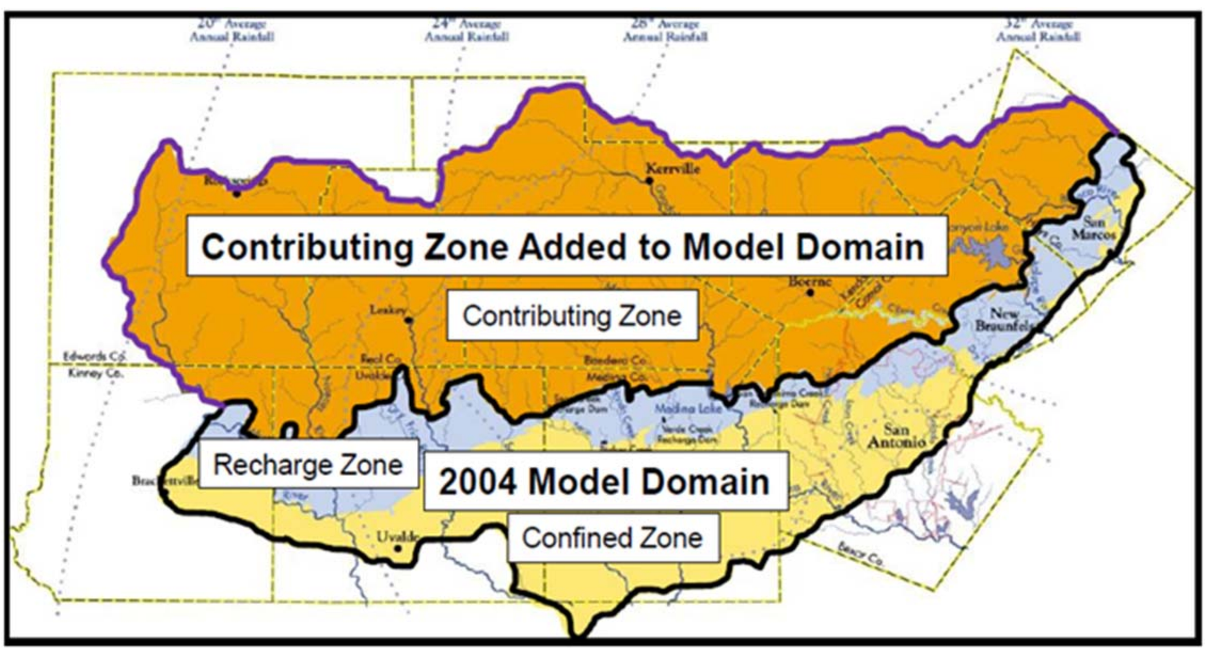

FIGURE 2-3 This map of the Edwards Aquifer region shows the 2004 model domain used in the MODFLOW model as well as the expanded domain used for the finite element model that includes the contributing zone.
SOURCE: EAA (2002).

The EAA's 2014 MODFLOW model was first calibrated using data from 1941 to 2000, then recently recalibrated using data from 2001 to 2009. The recent efforts took advantage of new pumping data for 2,719 permitted wells. Rather than using the parameters from the previous modeling period, additional adjustments were made to recharge and initial water levels to improve the match for the 2001-2009 calibration. Several different data sets from December 1973 to December 2000 were used for the initial head, and the recharge was also varied using the original and 8 different adjustments (see Table 2-2).

TABLE 2-2 Modifications to recharge tested during 2014 MODFLOW runs to calibrate to the 2001-2009 data set. Note that although the table refers to "verification run," these efforts were not "verification" but another calibration.

Verification Run #	Recharge Data Set	Initial Head Distribution
1	Adjusted Recharge & Blanco R Recharge Peak Cut	Dec-00
2	Adjusted Recharge & Blanco R Recharge Peak Cut	Nov-00
3	Adjusted Recharge & Blanco R Recharge Peak Cut	Dec-78
4	Adjusted Recharge & Blanco R Recharge Peak Cut	Dec-73
5	USGS Estimated Recharge Deliverable (by Puente, 1978)	Dec-78
5-2	USGS Estimated Recharge (by Puente, 1978)	Jun-76
6	Adjusted Recharge (after Lindgren et al., 2004)	Dec-78
6-2	Adjusted Recharge (after Lindgren et al., 2004)	Jun-76
7	Adjusted Recharge & Blanco R Recharge Peak Cut	Dec-78
7-2	Adjusted Recharge & Blanco Recharge Peak Cut	Jun-76
8	Leona Springs Property Changes with Adjusted Recharge & Blanco R Recharge Peak Cut	Dec-78
9	Adjusted Recharge & Blanco Recharge Cut + Barton Springs Segment Elimination	Dec-78
9-2	Adjusted Recharge & Blanco Recharge Cut + Barton Springs Segment Elimination	Jun-76
10	Adjusted Recharge & Blanco Recharge Cut at Daily Time-Step Simulation	Dec-78
10-2	Adjusted Recharge & Blanco Recharge Cut at Daily Time-Step Simulation	Jun-76
11	Adjusted Recharge & Blanco Recharge Cut - Run with Newton-Raphson Solver	Dec-78
11-2	Adjusted Recharge & Blanco Recharge Cut - Run with Newton-Raphson Solver	Jun-76

SOURCE: Winterlee (2014b).

The model predicts water level to compare with 423 observation wells and spring flow at seven targets distributed from east to west across the aquifer. The well targets are distributed across both the recharge zone and the confined zone of the aquifer, but with higher density in the eastern third of the aquifer. Distributing the calibration targets strengthens the model calibration. Model results were compared to monthly measurements, which is the finest timescale used in this modeling.

Some observations from these calibrations (found in Winterlee, 2014c) illustrate both the strengths and weaknesses of the modeling. Spring flow at Comal Springs tended to have better fits than at San Marcos Springs; Well J-17 was better than Well J-27, and the well water levels had better fits than the spring flows. Linear correlation coefficients (R^2) between observed and modeled heads and spring flows varied between 0.5 to 0.9. Modeled spring flows between 1947 and 2000 for San Marcos and Comal Springs were presented for both a diffuse and a conduit model. The residuals between observed and modeled flows varied over the time period but commonly reached 50 to 100 cfs (positive or negative), which is of the order of the minimum springs flow objectives in the HCP. Both the conduit and diffuse models tended to underpredict low flows at San Marcos Springs, although the fit improved in the last decade of the modeling

period, from errors of 50 cfs to 10 cfs or less (Figure 2-4). High flows were both under- and over-predicted. At Comal Springs, the conduit model tended to overpredict the low flows by 10 to 20 cfs in the period after 1976 (Figure 2-5). The diffuse model fit low flows better in this time period. For high flows at Comal, both under- and over-prediction were observed and the conduit model tended to have higher flows at the peak than the diffuse model. Conceptually, conduit flow models should provide faster flow of water from west to east and improve short term responses such as peaks and low flows or response to changes in recharge. Further discussion of how conduits and barriers are used in the model is in a following section.

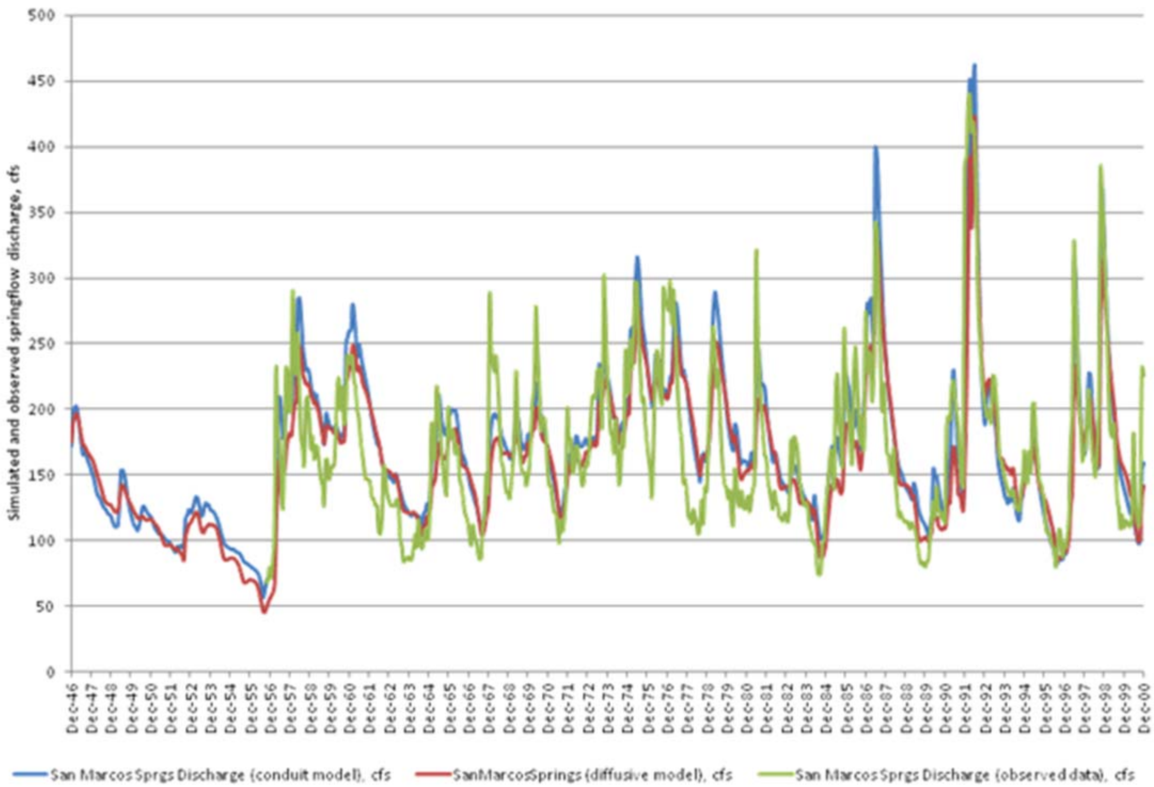

FIGURE 2-4 Actual and predicted San Marcos spring flow, comparing the EAA 2014 MODFLOW model (labeled the conduit model) and the older USGS MODFLOW model of Lindgren (2006) (labeled the diffuse model).
SOURCE: Winterlee (2014c) Slide 64.

The MODFLOW model was used to test management scenarios under conditions intended to replicate the drought of record (Figure 2-6). The simulations show that the highest level of mitigation was needed to keep the spring flow at Comal Springs above 30 cfs (Figure 2-7). That is, voluntary irrigation suspension (VISPO), municipal water conservation (Conservation), aquifer storage and recovery (SAWS ASR) and Stage V emergency reductions (Stage V) were all needed, with ASR making the largest contribution to predicted spring flows.

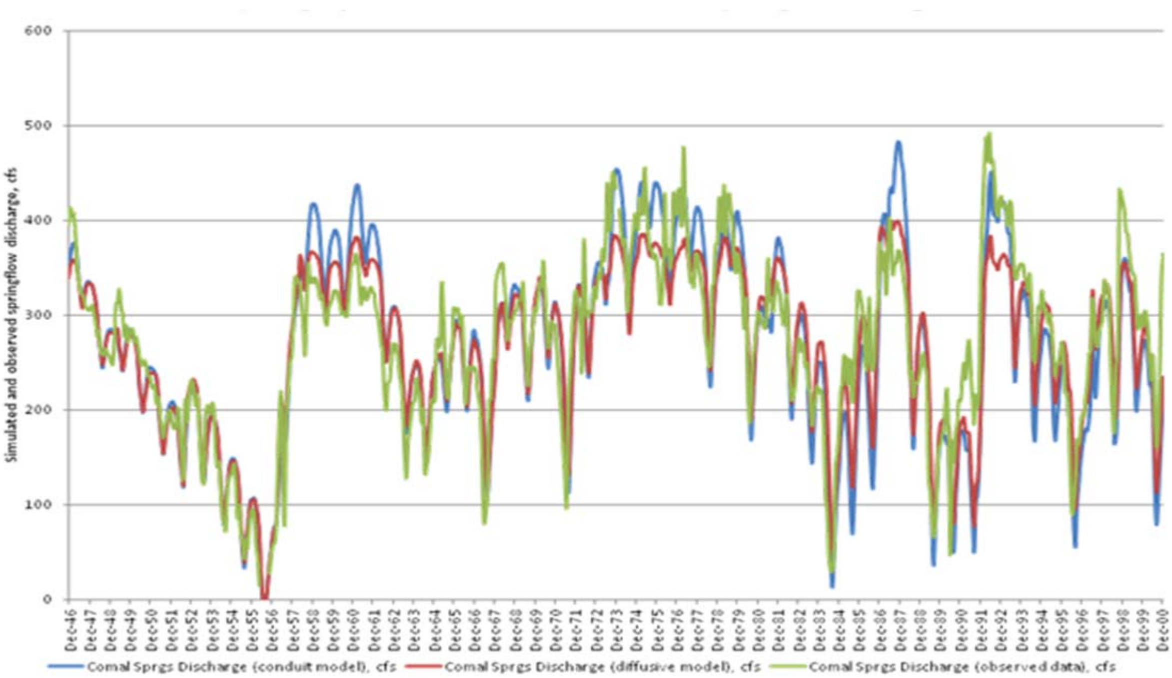

FIGURE 2-5 Actual and predicted Comal spring flow, comparing the EAA 2014 MODFLOW model (labeled the conduit model) and the older USGS MODFLOW model of Lindgren (2006) (labeled the diffuse model).
SOURCE: Winterlee (2014c) Slide 66.

FIGURE 2-6 Spring flow protection measures in the HCP and included in the MODFLOW model. The actual numerical changes made to pumping or additional inputs required to represent the four spring flow protection measures were not provided.
SOURCE: Winterlee (2014a).

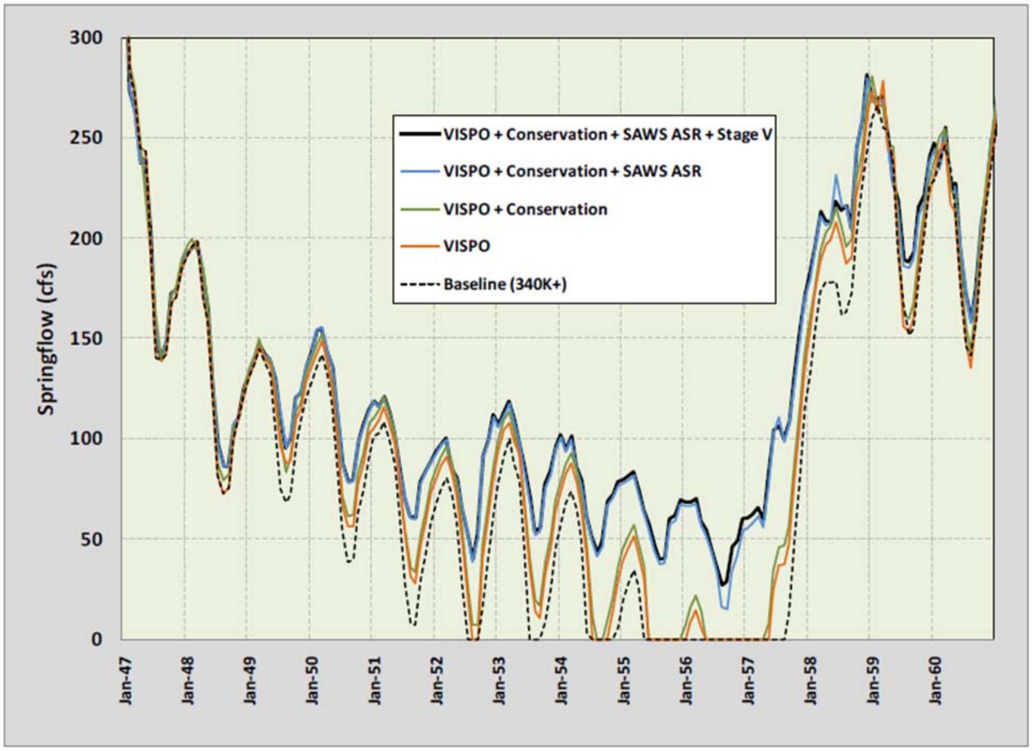

FIGURE 2-7 Modeling runs from the HRD report (Appendix K of the HCP) showing predicted Comal Springs discharge under the different management scenarios shown in Figure 2-6.
SOURCE: Winterlee (2014a) and EARIP (2012).

Although the MODFLOW model has provided a valuable tool for improved understanding of the Edwards Aquifer flow system and evaluation of management scenarios, there is uncertainty about the accuracy of the model predictions for a number of reasons. First, uncertainties in recharge and pumping can hamper calibration. For example, the lack of detailed information on pumping in the extensive well network of the Edwards region has limited the time-step size for transient modeling to monthly time steps, which in turn may limit the ability of the model to provide daily predictions for the HCP. Second, there is uncertainty in every model about heterogeneity in hydraulic conductivity, but this can be particularly troublesome for karst aquifers. There has been debate among those involved in modeling the Edward Aquifer about how to model karst conduits as well as fault barriers, both of which are important to producing a well-calibrated model. Third, the lack of a validation period for the MODFLOW model limits the confidence in model predictions. Fourth, there has been little documented uncertainty or sensitivity analysis for the MODFLOW model, although many techniques are available and are discussed further below. Finally, the scenario testing has thus far been limited to the drought of record. The model does not need to be limited to this scenario and one of the benefits of modeling is evaluating multiple factors including potentially more severe system stressors.

It is clear that extensive work has been conducted to model the Edwards Aquifer. Given the large scale and complexity of the aquifer, it is likely that data limitations and conceptual model issues will continue to arise. Thus, the MODFLOW modeling effort should be viewed as a work in progress and not a final product.

Finite Element Model Development

At the time of the writing of this report, development of a finite element (FE) model of the Edwards Aquifer is underway using the FEFLOW code. The purpose of developing an alternate groundwater model, according to the HCP, is to reduce uncertainty in the modeling results and increase the reliability and the defensibility of the model projections of aquifer and spring flows. Another reason for developing a second model of the Edwards Aquifer, although this is not a stated in the HCP, would be to capitalize on the unique features available in FEFLOW. The finite-element model is more appropriate for aquifers with complex hydrostratigraphy because it is not limited by the rectangular model cells typically used in finite difference models such as MODFLOW. In addition, standard MODFLOW models represent the porous medium as having relatively slow laminar flow, whereas the flows in the conduit networks such as those found in the Edwards Aquifer may occur under turbulent conditions. Some of the recent finite element models of groundwater systems allow the users to simulate turbulent flow in conduits, such that the simulation of fate and transport of flow and contaminants in such models are deemed more accurate for systems where both laminar and turbulent flows are present. The treatment of discrete flow features in FEFLOW is quite comprehensive allowing the user to implement a variety of geometries, phreatic and non-phreatic conditions, as well as three flow types using Darcy, Hagen-Poiseuille, and Mannings-Strickler equations. Various forms of flow equations used in FEFLOW enables it to simulate flow through porous media, pressure flow through geometries idealized as pipes or parallel plates, and open channel flow in both surface and subsurface features. FEFLOW's capability for modeling anisotropy and discrete flow features (Diersch, 2014) has been demonstrated in the Florida Aquifer in North Florida (Meyer et al., 2008).

In support of the finite element model, SWRI was also asked to further refine conceptualization of the Edwards Aquifer. Some of the suggested model improvements described in the statement of work include (Green et al., 2014):

- expansion of the model domain to include the contributing zone
- refinement of boundary conditions
- development of a refined hydrostratigraphic framework model, fault and conduit characterization
- correlation analyses to quantify the relationship between recharge events and aquifer response
- characterization and measurement of discharge mechanisms including paleo-stream underflow
- inclusion of both conduit and diffuse flow

These refinements are appropriate goals and could be applied to other Edwards Aquifer models as well. Not all of these refinements had been incorporated into the models as of the May 2014 presentation to the Committee.

The following brief assessment of the FE modeling effort is based primarily on presentations from the SWRI as well as progress reports of model development to the EAA (completed in May 2013, November 2013, and February 2014). Suggested improvements to the conceptual model are discussed in a later section on Future Directions, since they are not specific to FEFLOW.

As of May 2014, the FEFLOW model consists of about 50,000 elements. It was originally constructed using the finite element code TRANSIN and was then converted to FEFLOW. The current model uses the same equivalent porous medium (EPM) approach that was applied in the EAA 2014 MODFLOW model; that is, high transmissivity zones are being incorporated to model rapid flow movement in known conduits. The FEFLOW model covers a much larger area, including the Trinity Aquifer to the north, to better account for cross aquifer contributions (see Figure 2-3). [The Trinity Aquifer has a lower permeability than the Edwards, such that most recharge into the Edwards is occurring instead through the outcrop of the Edwards Aquifer. Nonetheless, some recharge through the Trinity may occur based on water budgets (Mace et al., 2000 reported in Lindgren et al., 2004) and geochemical mixing models (Musgrove and Crowe, 2012).] The FE model has a time step of one month, although there have not been any studies to determine if this is adequate to simulate the rapid transfer of flow from source areas to springs that are of interest. The period of calibration is 2002 to 2011.

Because modeling was still in progress during the review period for this report, the Committee can say little about the results of the modeling efforts. However, it can address the stated purpose of having another groundwater model, which was to make comparisons between the MODFLOW and FEFLOW model results and thereby reduce uncertainty. This purpose cannot be achieved under the current modeling strategy. The two models, developed using two separate codes, will each have their own inherent uncertainty, which cannot be understood by a comparison of the two. Rather, uncertainty should be addressed using a variety of methods that are discussed extensively below. The two models could be used to compare differing recharge strategies, but the same could have been achieved by continuing to use only MODFLOW. Theoretically, the complex and nonlinear features of the fractured system of the Edwards Aquifer can be represented more accurately using a finite element mesh, but no such plans were presented to the Committee, and similar features are available in upgrades to MODFLOW (see MODFLOW-USG discussion below).

Importance of Conduits in Modeling Karst Aquifers

One of the key questions and a topic of extensive discussion is how conduit flow should be represented in Edwards Aquifer models. Differing opinions exist within the public, water-management, and scientific communities about whether there is enough evidence to support the placement of conduits in the model and if so, how it should be done.

Several lines of evidence suggest the importance of conduits in this system. Localized dye tracings indicate very high water velocities in the subsurface, and additional dye tracing is underway (Johnson et al., 2012). Flashy responses in wells and springs are also evidence of conduit flow. Lindgren et al. (2009) discussed improved model fits at high and low flows when conduits are included.

The current EAA MODFLOW model, originally constructed by the USGS (Lindgren et al., 2004) and later revised by the EAA (HDR, 2011), simulates conduits in selected areas with zones or rows of finite-difference, Darcian-flow cells with anomalously high permeability. This conceptualization is illustrated in Figure 2-2c. The simulated conduits in the model by Lindgren et al. (2004) were 0.25 miles wide, or the width of a model cell. Although this is much wider than actual conduits in the aquifer, these features were narrow relative to the scale of the model

area and were used to simulate the general characteristics of a conduit system rather than the specific physical processes of flow in actual karst dissolution features. Fluid flow in these zoned features was simulated in the same way as in the surrounding cells, except with higher permeability, although not reaching a true conduit velocity.

Several other methods of representing conduits in the models are possible. Pipe or line elements are small features with conduit properties inserted at discrete locations as indicated by Figure 2-2e. These pipes simulate flow on the basis of laminar flow equations with high velocity; also, turbulent flow is now available or in development for certain codes. The pipes simulate open-channel flow when not fully saturated. Within such models, the locations of both high velocity features and contrasting fault barriers are highly uncertain. Another option for representing conduits is to treat their locations as uncertain but just provide dual permeability in representative layers (Panday et al., 2013) as illustrated in Figure 2-2d. The dual permeability model nonetheless requires characterization of each media (the matrix and the higher permeability conduit zone) and an exchange term for communication between the layers. A final option is to use an equivalent porous media (Figure 2-2b) with a slightly higher permeability than rock without conduits and perhaps some anisotropy if there is a preferential flow direction.

The model presentations to the Committee do not make it clear to what extent conduits have been included in the current modeling, and controversy surrounds the choice of method. The use of conduit features that are larger than observed to approximate the behavior of conduits seems unrealistic and raises concern that they might overestimate conduit behavior. The EAA also indicated that the locations of such features are non-unique in model calibration, which makes the model open for criticism (EAA/NRC, 2014). Despite this, the Committee feels that the rapid aquifer response to recharge and management actions will not be adequately simulated without the use of conduit-like features, especially if the modeling effort moves to a shorter time step in the future (see subsequent discussion).

FUTURE MODELING DIRECTIONS

Both the MODFLOW and FEFLOW modeling efforts presented to the Committee have showed a high level of sophistication and considerable effort to capture the complex flow system of the Edwards Aquifer. The Committee has a number of suggestions (1) about changes being made to the conceptual model and (2) to help quantify uncertainty and increase the ability of the models to make predictions.

Continue Improvements in Recharge Estimates

Groundwater recharge from the land surface (hereafter, recharge) is the most sensitive parameter affecting spring flow for normal or above normal precipitation periods (Lindgren et al., 2004). Given the importance of recharge for a groundwater system, improving the accuracy of recharge estimates has the potential to improve the model considerably. Recharge to the Edwards Aquifer occurs through groundwater infiltration of streams that cross the recharge zone and from direct precipitation on the recharge zone (Puente, 1978; Lindgren et al., 2004; EAA, 2013). Additionally, the EAA operates four structures within the Edwards Aquifer recharge zone that capture runoff and induce groundwater recharge as described in EAA (2013).

The original Edwards Aquifer model (Lindgren et al., 2004) and subsequent MODFLOW efforts (EAA, 2013) have all relied on a method for estimating recharge described by Puente (1978) (http://tx.usgs.gov/projects/aquifer_springs/estimatedrecharge.htm). The Puente method uses streamflow measurements upstream and downstream from the recharge zone and estimates tributary inflow to determine stream recharge on a monthly basis; this method also estimates base flow and recharge from direct precipitation. Evapotranspiration is neglected in this method, but this has been deemed acceptable because much of the recharge comes from large storms for which evapotranspiration is negligible (personal communication, Richard Slattery, USGS, 2014). Recharge estimates from the Puente method were applied to a model "testing period" that followed the calibration period, which was an attempt at model validation (Lindgren et al., 2004); however additional parameter adjustments were needed for this testing period, and therefore, the model was not truly validated. This raises questions about the accuracy of the recharge estimates.

Currently, the EAA is developing an improved method to estimate recharge by application of the Hydrological Simulation Program—Fortran (HSPF; http://water.usgs.gov/software/HSPF/). HSPF is a watershed streamflow model that simulates continuous streamflow resulting from system inputs of continuous precipitation and other meteorological data. HSPF also simulates soil moisture, overland surface runoff from rainfall, shallow groundwater flow toward streams (interflow), groundwater inflow to streams (base flow), snowpack depth and water content, snowmelt, evapotranspiration, groundwater recharge, stream channel routing, reservoir routing, and water-quality parameters. The Puente method does not account for most of these processes and, therefore, is much simpler than HSPF. If the HSPF model is calibrated to observed streamflow, the component of groundwater recharge simulated by HSPF can be used as an estimate of groundwater recharge for the Edwards Aquifer groundwater-flow models. Also, the HSPF model can be used to estimate streamflow entering the Edwards Aquifer recharge zone from the north, a function that cannot be performed with the Puente method but would be necessary to estimate recharge for a hypothetical precipitation scenario, such as drought.

It is important that the parameters of the HSPF model be consistent with the intricacies of a karst system (Ford and Williams, 2007). The recharge zone for the Edwards aquifer consists of karst rocks that allow fast infiltration of precipitation and surface water through fractures and dissolution openings such as caves. Streams flow onto the Edwards aquifer recharge zone from the north (Edwards Plateau) and sink into the Edwards aquifer (Puente, 1978). A stream that sinks into the ground indicates that the groundwater table is below the stream bed, and, if possible, the parameters of the HSPF model should be set accordingly to allow fast infiltration of surface water. Accurately estimating the temporal changes in recharge is essential for simulating changes in spring flow.

Clear Creek Solutions, Inc. (2012, 2013) has used HSPF to simulate streamflow for selected sub-basins that contribute to the Edwards Aquifer in order to estimate groundwater recharge. Results from this modeling have been compared to use of the Puente method for estimating recharge, as shown in Figure 2-8 below. Note that there are large differences in the recharge estimates, especially at higher recharge values. The Committee recommends continued development and testing of the HSPF model for estimating recharge. Uncertainty analysis, as discussed in a subsequent section, will provide guidance as to which recharge method to use.

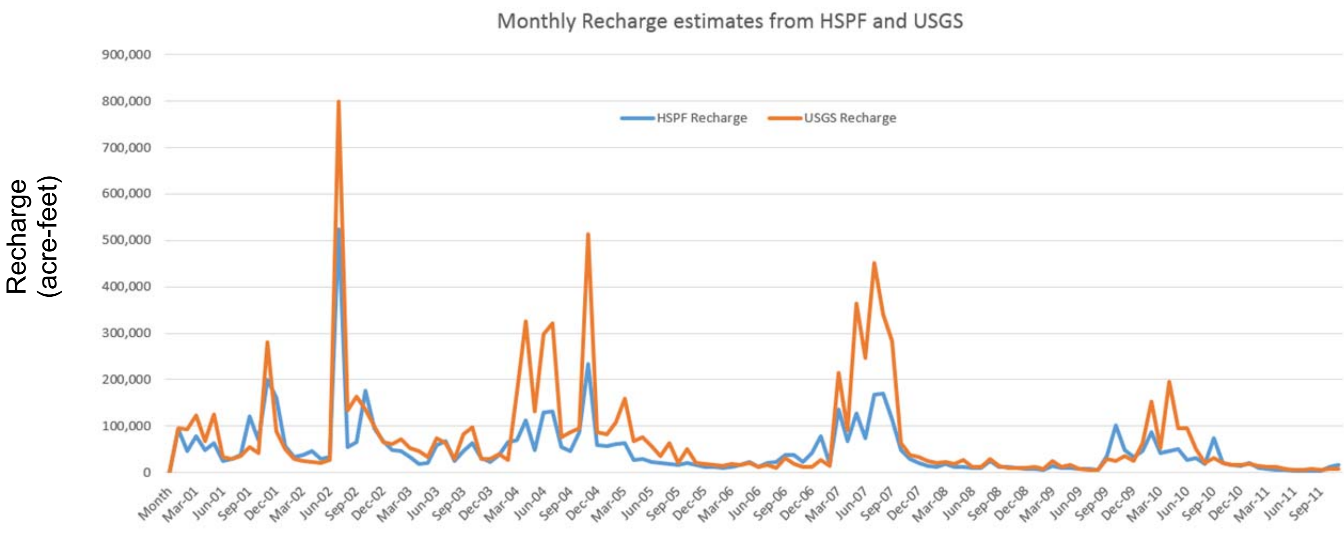

FIGURE 2-8 Comparison of recharge estimates from the Puente method and HSPF.
SOURCE: Winterlee (2014d).

Improve Conduit Representation

As stated previously there are a range of options for representing conduits, from no conduits to discrete pipe flow simulation with high velocity paths (Figure 2-2). Given the evidence that conduits play a role in karst aquifers such as the Edwards, it is suggested that conduits be represented in the model to a greater degree than what was presented to the Committee, despite uncertainty about conduit locations, diameters, lengths, and other properties. Uncertainty is associated with all model features, and can be evaluated using uncertainty analysis (discussed in the following section).

Although the EAA currently does not have an objective to accurately simulate groundwater velocities measured from dye tracing, this capability would enhance the defensibility of a model and thus would be a useful long-term goal—one in which conduits will be necessary. The ability to simulate these flow velocities in future models also would allow the simulation of current or potential transport of contaminants to the springs, such as herbicides, insecticides, and volatile organic compounds frequently detected in Barton Springs (Mahler et al., 2006). Groundwater-age dating and analysis of specific conductance are other possible methods that could help to estimate conduit locations (Long et al., 2008).

A great deal of work has already been conducted to better identify and characterize conduits, both in terms of modeling and field programs such as tracer tests. The Committee reiterates the need to continue attempts to characterize conduits and determine their importance in discharge predictions from hydrologic models of the Edwards Aquifer. This notion was recently reinforced by the Groundwater Modeling Review Panel to the EAA, who recommended adding conduits to the finite element model (Saar, 2014). Conduits will become even more important for simulating daily spring flows with future models that have daily time steps (see

later discussion on time steps). Effective communication to the public concerning the importance of conduits despite the uncertainty of conduit locations will be important.

Uncertainty Analysis

All models have some level of error in their predictions. Quantifying this uncertainty, although a challenging task in many cases, increases the model's defensibility and can provide a reasonable estimate of model error, which is important information when using a model for management decisions. In none of the presentations to the Committee have the results of the MODFLOW model been presented with errors bars or some other indication of the uncertainty in the predictions. Although EAA staff say that they intend to formally account for uncertainty, no document has been created laying out the methods. Furthermore, given that the calibration errors observed for the MODFLOW model are as large as the minimum required spring flows in the HCP, it is imperative to better understand model and input uncertainties and how they translate into uncertainties in the simulated management actions. Hence, this section describes ways for the EAA to formally consider uncertainty in their hydrologic models, both for MODFLOW and the finite element model.

In the section below, quantitative methods are described that can assess (1) the uncertainty of individual parameters, groups of parameters, or the nonlinear interactions thereof (parametric uncertainty); (2) the uncertainty of model predictions (predictive uncertainty); and (3) the uncertainty associated with how the groundwater system is conceptualized (conceptual model uncertainty). There are other types of uncertainty that are not discussed here, including the uncertainty associated with the accuracy and fidelity of numerical algorithms chosen for the model and the measurement uncertainty associated with the data used to calibrate and validate the numerical models. In the Committee's opinion, these latter types of uncertainty are likely to be of lower magnitude and less important to improving the current modeling effort of the Edwards Aquifer. The focus here is on methods that members of the Committee have found useful in similar systems. To be most useful for EAA managers, they are presented in order from easiest-to-implement to most complex: sensitivity analysis, formal model validation, PEST predictive uncertainty analysis, and the ensemble method. Some of these methods can address multiple types of uncertainty, as will be discussed. The section ends by discussing the reduction in predictive uncertainty that could result if new data were collected and what those data should include.

Sensitivity Analysis

Parameter sensitivity analysis is helpful in assessing model uncertainty quantitatively because large parameter sensitivity commonly results in large model uncertainty related to those parameters. If a parameter has large inherent uncertainty but the model is not sensitive to it, then the uncertainty of that parameter might not be critical. An example of this situation is where inflow from another aquifer has large inherent uncertainty but accounts for only a small component of total system inflow. For example, inflow to the Edwards Aquifer from the Trinity Aquifer is estimated to be 12,000 acre-feet per year but with a large uncertainty, ranging from 2,000 to 30,000 acre-feet per year. If this range is equivalent to only about 0.3 to 5 percent of the

total aquifer inflow, the model would not be highly sensitive within this range. If, however, a parameter has large inherent uncertainty and also results in large model sensitivity, then that parameter is critical and contributes substantially to model uncertainty.

Although the original MODFLOW model (Lindgren et al., 2004) included a sensitivity analysis, none appears to be associated with either of the current models in progress. According to the EAA's presentation to the Committee in May 2014, model parameters in the western part of the model and groundwater exchange with other aquifers are thought to account for the largest inherent parameter uncertainty. A well-designed, formalized sensitivity analysis could be used to indicate the model sensitivity to these parameters as varied within the ranges of their inherent uncertainty (e.g., Campbell and Coes, 2010). For example, each parameter or group of parameters could be increased by 1 percent, and the resulting change in spring flow at each spring of interest could be quantified. Parameter categories that should be included in a sensitivity analysis are recharge, horizontal and vertical hydraulic conductivity (K_h and K_v), spring conductance values that influence the rate of spring flow, and those related to fracture flow, conduit flow, and barrier faults, if applicable. A generalized sensitivity analysis might consist of only these parameter categories, where all model values within each category are varied as a group for the entire model area, and the sensitivity by category is reported. In addition, more detailed approaches might include testing the sensitivity of individual spring conductances and K_h or K_v within subdivided model areas with respect to individual springs, especially for those of particular interest. In addition to varying all parameters equally, a plausible range for particular parameters of interest might be estimated in terms of the inherent uncertainty, as previously described. An interim detailed sensitivity analysis for the current MODFLOW model would provide additional guidance on calibration and how to better focus continued hydrogeologic characterization efforts. SENSAN is a utility that automates the tedious effort that is otherwise required to do sensitivity analysis (Doherty, 2005).

The simple sensitivity analysis discussed above, sometimes referred to as "one factor at a time" (OAT), is a useful general assessment but has the major limitation of neglecting nonlinear parameter interactions. To account for these interactions, and thus provide a better assessment of the relative parameter sensitivities, the Morris method can first be used to identify the most sensitive parameters, which then are evaluated in depth by the FAST method (Morris, 1991; Saltelli, 1999; Muñoz-Carpena et al., 2007; Srivastava et al., 2014). Nonlinear parameter interactions also can be assessed by methods described in Doherty et al. (2010) that, additionally, quantify predictive uncertainty, as discussed below.

Formalizing Model Validation

Validation refers to executing a calibrated model for a period of the data record not used in the calibration and comparing the results to measured data (e.g., groundwater levels and spring flows). The model's goodness of fit to data for this period provides an estimate of the model's predictive accuracy for simulation of a stress scenario, such as increases in pumping or drought, for a period of time equal to the validation period. This validation is conditional until future data are collected and tested with the model. If the predictive accuracy determined by validation is considered unacceptable for the EAA's management purposes, then selected conceptual-model assumptions should be adjusted in the numerical model, which would then require recalibration (e.g., see Long and Mahler, 2013).

The MODFLOW model described by Lindgren et al. (2004) was calibrated to data for 1947 to 1990, and there was an attempt to validate the model to data for 1991 to 2000 (i.e., the "testing period"). Unfortunately, during this exercise additional adjustments to storativity and hydraulic conductivity values were made for areas near recharge zones, such that this was merely additional model calibration, not validation. The EAA's current MODFLOW model was calibrated to data for 1941 to 2000, and again an attempt was made to validate the model to additional data for 2001 to 2009 (Winterlee, 2014b). However, further adjustments to recharge rates were made for this period to achieve an acceptable model fit, and similarly to Lindgren et al. (2004), this was merely additional model calibration. Having a validated model will allow the EAA to make better predictions of spring flow or groundwater-level responses for future scenarios. Box 2-2 describes how to determine confidence intervals based on validation-period residuals in order to quantify model uncertainty.

Box 2-2
Confidence Intervals Based on Validation-Period Residuals

Information about model uncertainty can be gained by estimating confidence intervals on the model validation, based on validation-period residuals. During validation, the residuals (or differences) between simulated and observed values are evaluated. A variety of metrics have been used for residuals in past Edwards Aquifer modeling efforts. For example, Lingren et al. (2004) reported the mean absolute difference, mean algebraic difference, and root mean square (RMS) error of these residuals for single water-level measurements and water-level and spring flow time-series data. The EAA reported the correlation coefficient for water-level and spring flow time-series data for the 2001-2009 simulation (Winterlee, 2014b). All of these metrics are useful for a dataset of single measurements or for a mixture of single measurements and time-series data; however there are other metrics that are more informative when assessing a simulated time-series record. The Nash-Sutcliffe coefficient of efficiency (E) (Nash and Sutcliffe, 1970; Legates and McCabe, 1999; Long and Mahler, 2013) is a useful measure of the similarity between simulated and observed time-series records. This metric compares the magnitude of residuals to the overall variability in the observed record and, therefore, puts these residuals in a meaningful context.

The validation-period residuals can be used to estimate confidence intervals on the model validation and thus convey information about model uncertainty. The first step is to calculate the standard deviation σ of all the residuals for the validation period. Then, plot the 95% confidence intervals for the validation period, which are at a distance of σ above and below the simulated spring flow. This assumes that the residuals are normally distributed and random. If, however, there is a relation between the magnitudes of residuals and the observation values (i.e., not random), then confidence intervals might be different for high, medium, and low flows, and these three categories could be plotted separately. These calculated confidence intervals can then be placed on simulated spring flow records for stress scenarios to show uncertainty of model predictions. It should be noted that these confidence intervals only apply to climatic, spring flow, and water-level conditions that are within historical ranges. Outside of these ranges the confidence intervals may be larger than those estimated. Also, these confidence intervals would be less certain for a prediction that extends beyond the length of the validation period.

PEST Predictive Uncertainty Analysis

PEST predictive uncertainty analysis, described by Doherty et al. (2010), requires that the inherent parameter uncertainty (i.e., range of each parameter's potential values) be estimated on the basis of expert knowledge. This parameter uncertainty is then propagated to model predictions, such as changes in spring flow in response to changing climatic conditions or increased groundwater withdrawals, which can provide an estimate of confidence intervals on predictions. The method is based on the assumption that model outputs are linearly related to model-input parameters, although nonlinear relationships can also be handled via null-space Monte Carlo analysis (Tonkin and Doherty, 2009) but are more computationally intense. For example, uncertainty of the average recharge rate might, by expert knowledge, be determined to be within ±10% of that estimated by HPSF modeling. A recharge multiplier could then be applied in the groundwater model to the overall estimated recharge and allowed to vary by ±10% for the PEST predictive uncertainty analysis. Similarly, potential variability ranges could be estimated for all other calibrated parameters, such as hydraulic conductivity, storage coefficient, specific yield, and specified inflows or outflows. In the PEST uncertainty analysis, the potential variabilities of all model parameters are analyzed simultaneously. Plans to incorporate PEST into the current modeling efforts were mentioned by EAA scientists, but no results were available for the Committee to review. However, an excellent example of this method applied to a groundwater model of the Edwards Aquifer is described in Brakefield et al. (2015), in which new insights into the saline-water transition zone were gained.

Ensemble Method

Another source of uncertainty is associated with the assumptions in the conceptual model. A comparison of different sets of conceptual-model assumptions in different versions of the same model code (i.e., an ensemble) can be useful in quantifying this uncertainty. The ultimate goal of this exercise is to select from the ensemble the model version that best answers management questions. The ensemble method is similar to the PEST predictive uncertainty analysis previously described, except that conceptual-model assumptions are tested rather than parameter values. Hartmann et al. (2013) and Long and Mahler (2013) describe this method of testing multiple conceptual models of karst aquifers.

One application of the ensemble method useful for the Edwards Aquifer would be to assess the uncertainty associated with the precise locations and characteristics of conduits. Conduits might primarily be large, single features, or they might be smaller features that are grouped into conduit zones. Thus, conduits could be simulated by large, discrete pipe-flow features but also could be represented by wider zones having high K_h values; these two differing assumptions could be tested in different model versions. Varying a conduit's location to the right or left (perpendicular to flow) in different model versions could be used to test its optimum location and to indicate the zone within which a simulated conduit can be moved without adversely affecting the goodness of fit. This zone could be shown on a map of the model area, possibly as error bars placed perpendicular to the conduit, to indicate uncertainty of the conduit's location. Also, the overall conduit network configuration in the model domain could be tested

by placing conduits in many different plausible locations or by generating different conduit networks stochastically, as described by Ronayne (2013).

The ensemble method can also be used to assess predictive uncertainty by comparing the model outputs from all plausible model versions to a stress scenario, such as drought. That is, an ensemble plot composed of multiple model outputs would show a range of spring flow responses to the same stress scenario. On the basis of this range of model outputs, error bars could be shown around the spring flow hydrographs that were simulated by the selected or preferred model version. This exercise would not necessarily show the full range of predictive uncertainty, but it would at least quantify a minimum uncertainty range. The higher the number of plausible model versions tested, the more the confidence one could have in the error bars.

Data Collection for Reducing Predictive Uncertainty

The EAA has been involved in a long-term hydrogeologic investigation of the Edwards Aquifer that includes data collection (see Box 2-3), conceptual-model development, and numerical modeling for many years and plans to continue this effort into the foreseeable future. Large resources are required to plan and collect new data; therefore, it is important to consider what new data would result in the greatest benefit to the reduction of the hydrologic model's predictive uncertainty.

Both the modeling and the field programs should consider further examination of dynamic responses of the aquifer due to seasonality, climate change, and urbanization. This is needed because if interpretations about connectivity or flow barriers are based on a particular set of hydrologic conditions, the resulting predictions may falter as the stresses to the aquifer change. In addition, modeling could be used to explore the sustainability issues such as how long does it take for a change in recharge to propagate to the discharge area? Given the difficulty, time, and expense in collecting data over the frequency and time intervals needed to explore dynamic responses, focusing on a particular location is also important. Examining the dynamics between Comal Springs and San Marcos in more detail is recommended due to the implications for management and previous data that show that connectivity between these two springs changes with flow conditions (EARIP, 2012). Modeling supported by field work including long-term monitoring, natural tracers, and other efforts discussed in Box 2-3 could greatly improve management response to system stress.

A method that addresses how data collection can reduce uncertainty is described by Fiennen et al. (2010), which is based on parameter sensitivities related to a prediction of interest. This method quantifies the reduction in model uncertainty that could be achieved by adding monitoring sites at specific locations. The utility PREDUNC, which is part of the suite of utilities available with PEST, is used to conduct the predictive uncertainty analysis. PREDUNC can be applied to models calibrated with PEST when pilot points, as described by Doherty (2005), are used to parameterize the model; if the model is parameterized by zones of uniform values (e.g., hydraulic conductivity), results of the analysis can be misleading (Fiennen et al., 2010). Therefore, this method should not be used with the MODFLOW model unless the model is recalibrated with pilot points.

Box 2-3
EAA Groundwater Monitoring Plans

According to the 2012 Hydrologic Data Report (EAA, 2013), monthly water level and spring flow data are collected in addition to precipitation measurements at locations across the aquifer. Recharge is estimated under a joint funding agreement with the USGS using precipitation and streamflow measurements reported across nine zones.

A work plan for hydrologic monitoring was not presented at the Committee's February 2014 meeting, but reports from the Aquifer Science Program were provided. These reports describe aquifer characterization efforts involving geophysics, tracer tests, potentiometric mapping, and proposed pumping tests.

The geophysical work includes evaluation of deep seismic data when available from oil company exploration, shallow seismic data to map gravel deposits that may lead to water bypassing Leona Springs, and borehole logs for new and existing wells. The borehole logging equipment is owned by EAA and is in use "almost weekly" (Geary Schindel, EAA, personal communication). The borehole logs help identify aquifer boundaries and fault patterns and can be used to conduct some aquifer characterization using borehole dilution tests.

The tracer tests have been used to try to map conduit connections. Noteworthy is that tracer has been observed to move across fault boundaries that originally were believed to be barriers to flow. Where tracer data are available, conduits or high permeability zones have been incorporated into models, although use of conduits in modeling is controversial, as discussed above. Tracer test results have been presented in reports from EAA and the USGS.

Pumping tests are planned to evaluate aquifer properties (transmissivity and storativity). These tests can also be located in such a way as to further identify fault behavior if water can be pulled across fault boundaries. Planning is underway to conduct pumping tests.

Another proposed area of study is evaluation of the San Marcos pool to better understand how its recharge is similar to and different from Comal Springs. The two springs do not show the same response to wet and dry periods (see Figure 14 in Appendix B of the HCP). Management of the pools is currently linked, but understanding the similarities and differences might improve strategies. The San Marcos pool report (Appendix B of the HCP) provides estimates that perhaps half of the spring water comes from flow paths that bypass Comal Springs, more in drought conditions. This water moves from west to east. Additional water comes from Hays County and comes from the northwest instead. Flow estimates indicate a significant amount of water comes from local streams recharging the aquifer and ending up in San Marcos (Johnson and Schindel, 2008 as reported in Appendix B of the HCP). However, this estimate is contradicted by geochemical modeling (Musgrove and Crowe, 2012) that used mixing models to estimate contributions from local and regional flow. They estimate that 10 percent of recharge to the San Marcos Springs comes from local streams. These contradictions lead to uncertainty in model conceptualization.

Projects for aquifer characterization are suggested and reviewed by an Aquifer Plan Science Advisory Board convened by the EAA, and many of the projects are directed toward model improvement. However, the work is conducted separately from the HCP. Furthermore, while the results from these studies are provided to the modeling group, it is not clear that modeling studies (e.g., optimization analysis) can or will be used to direct hydrologic studies.

Refining the Time Step and Scale of Modeling

The use of the monthly time step in the hydrologic modeling is problematic for a number of reasons. First, it does not align with the finer time step of the ecological models to be

developed in support of the HCP, most of which are daily. According to the HCP, the groundwater models will produce "reliable and defensible" spring flows and the ecological models will be "linked with the groundwater model" (EARIP, 2012; p. 6-5 and 6-7). Using different temporal scales for the two modeling efforts weakens the linkage. [It should be noted that the ad hoc adjustment to monthly spring flows to estimate a daily average (EARIP, 2012; p 4-49) is *not* supported by established method]. Second, although the HCP specifies the minimum required flow rates at the springs mostly in terms of monthly averages, some of the flow-related goals within the HCP are expressed as daily average flows at Comal or San Marcos Springs (e.g., a minimum of 30 CFS at Comal Springs, p. 4-5, EARIP, 2012). Third, when an aquifer responds rapidly to flow events because of either high transmissivity or conduit flow, a larger time step such as a month may not adequately capture the aquifer response. Some of the tracer data presented to the Committee at the May 2014 meeting show that the "lag time" in some areas could be as little as 15 days. Clearly there is a disconnect between what can currently be predicted with the hydrologic models and the future needs of the HCP.

Mathematical models require an appropriate time step to reduce numerical errors in the solution of the basic equations of flow describing the system (Wang and Anderson, 1982). The Committee is not aware of any formal investigation such as a convergence test with different time steps to ensure adequate performance of the model. This is an essential step in the model verification process. The use of a smaller time step may be required if and when the FEFLOW or other model is used with discrete flow features and under turbulent flow conditions.

One of the difficulties presented by shortening the time step is that pumping rates for the hundreds of wells in the Edwards Aquifer region are only available on a monthly basis. To be sure, the data collection for all these wells is daunting, although improvements in automatic monitoring are underway. Modeling should be used to help focus the data collection efforts and make this task more manageable (see previous section). For example, an evaluation of model sensitivity for key areas and ranges of rates could identify a subset of wells where the gathering of detailed (i.e., daily) pumping rates would be most valuable.

Telescoping models could be developed in critical areas to address a number of issues identified in this chapter, such as the need for improved spatial resolution near the springs. Telescopic mesh refinement is the use of a refined mesh in an area of interest; it differs from refining a portion of the grid because the telescoped model can be modeled apart from the larger, regional model (Mehl et al., 2006). The alternate strategy of refining a portion of the grid within the larger model can lead to finite-difference meshes with long narrow cells that are numerically difficult or can have complicated finite-element geometries with large computational cost. The telescoped model has interpolated parameters and boundaries from the regional model, so information is exchanged between the two models. Improved linkage between the larger and smaller scale grids has been the subject of recent research (e.g., Dickenson et al., 2007).

Telescoping meshes have been widely used (Mehl and Hill, 2002) to increase accuracy for pumping, heterogeneity, and transport. For example, Ward et al. (1987) developed three meshes for a remediation site in Ohio at scales of 15 km (regional scale), 3 km (local scale), and less than 0.3 km (site scale). They added heterogeneity at the local scale, and provided more detailed remediation at the site scale to improve contaminant transport predictions.

The benefits of telescoping models if developed for the HCP include being able to incorporate detailed pumping rates, which require a finer time step, and better representing

subsurface heterogeneity such as conduit pathways. Both of these refinements would be difficult to implement over a large regional model. Furthermore, some of the hypothetical scenarios for future conditions could be tested on a refined model in order to more efficiently evaluate the impact of parameter sensitivity.

The strategy for developing telescoping models would require that boundary conditions be transferred from the regional model to the telescoping model. The current design of the finite element model to calibrate one pool at a time (working from west to east) and determine water transfer between the pools has a similar approach. This transfer could be refined and the focus could be turned to the eastern pools (San Marcos and Comal) where the ecological triggers are located. The model for the regional aquifer could have a monthly time step, and the boundary conditions transferred to the finer mesh would reflect inputs with a longer memory such as recharge. However, the smaller time step of the telescoping model could be used to incorporate stresses that change more abruptly, such as pumping, and to be better aligned with the needs of the ecological modeling. Furthermore, a more refined time step would more accurately implement some of the hypothetical scenarios that need to be tested for predictive modeling of future stresses. A similar refinement can occur for spatial parameters. Even though the exact conduit locations are still problematic, model sensitivity to heterogeneities could be evaluated better in a telescoping grid. In other words, conduits and barriers could be included in a small region and related to site specific tracer tests or pumping tests at this scale.

Future Code Selection

Currently there are two models with two competing codes running for the Edwards Aquifer. As stated previously, the HCP-stated purpose for developing an alternate groundwater model was to "reduce uncertainty in the modeling results and increase the reliability and the defensibility of the projections of aquifer and spring flows." Compared to the proven methods for conducting sensitivity and uncertainty analysis discussed above, having two models is not generally useful for quantifying predictive uncertainty. Furthermore, it is not clear why the HCP specifically called for the development of a new finite element model as opposed to further improving the existing MODFLOW model. Usually model selection is driven by features that improve model conceptualization. Theoretically, the complex and nonlinear features of the fractured system of the Edwards Aquifer can be represented more accurately using a finite element mesh. However, new advances in unstructured finite difference grids are now available to users. Specifically, MODFLOW-USG (Panday et al., 2013) overcomes many of the limitations of previous MODFLOW versions such that it may be considered as an alternative to FEFLOW. For example, MODFLOW-USG models can now be constructed with a variety of grid geometries and are no longer limited to rectangular grids. Nested or telescoping grids are easily added to sections of a larger (regional) model, as well as linear elements (connected linear networks) that can be used for conduit flow. MODFLOW-USG is becoming more widely available with pre- and post-processers and provides an open source platform that has been frequently used for the Edwards Aquifer (Table 2-1).

It is not the Committee's intention to advocate for a particular code. However, given that both MODFLOW-USG and FEFLOW are available to perform the necessary tasks, there is not sufficient justification for running multiple codes. Focusing on a single model that incorporates

all of the necessary features, whether finite element or finite difference, would improve efficiency. Whatever code is chosen, the conceptual model improvements described in the FEFLOW model section should be incorporated.

CONCLUSIONS AND RECOMMENDATIONS

The hydrologic modeling effort has shown continuous improvement in both the use of models and the incorporation of new data. For example, the modelers recognized the need for improved estimates of recharge and explored use of HSPF, which the Committee encourages them to continue for the entire area that contributes streamflow to the recharge zone. The importance of more accurately understanding recharge was also demonstrated during the investigation of the potential recharge through adjacent aquifers. Pumping data are now more frequently collected (expanding from yearly to monthly) to improve model inputs. Connections between pools are being explored in order to construct water budgets that will help understand how one region can affect another. Through calibration, the modelers have simplified the modeling of barrier faults to key locations where hydrologic influence has been identified. These and other improvements to the conceptual model of the Edwards Aquifer are ongoing. Below, the committee identifies areas that merit further attention and makes recommendations for future work that will build upon the EAA's strong foundation of modeling and data collection efforts.

The EAA could gain efficiency by moving toward a single model that incorporates the best concepts from existing modeling efforts. Continued development of "competing" models is inefficient, unnecessary, and inferior to the methods described above for assessing model uncertainty.

In developing a rationale for which model to use going forward, the future model should be able to incorporate as much knowledge as possible from past modeling efforts and data collection. Any new model selected should have features that benefit the conceptual model, such as telescoping meshes and linear features for conduits and barriers.

Model uncertainty needs to be quantitatively assessed and presented in formal EAA documents. Quantifying model uncertainty increases a model's defensibility and can provide a reasonable estimate of model error, which is important information when using a model for management decisions. Uncertainty has been mentioned in some of the EAA's modeling reports, but is not a standard feature in their documentation of modeling results, including presentations to the Committee. Specific recommendations include conducting more explicit sensitivity analysis; validating the groundwater model by testing its predictive abilities using data from a time period not included in the model calibration; using additional calibration and validation metrics; and having confidence intervals presented with modeling results when practical.

Moving forward, more attention should be paid to the modeling of conduits. While there are a number of methods for incorporating conduits into groundwater models, the most appropriate one for modeling the Edwards Aquifer has not been clearly identified. Both of the models in use (MODFLOW and FEFLOW) offer choices for how to incorporate karst features as well as fault barriers. It seems likely that at some future stage, especially if finer time steps are used, conduits will be needed in order to improve model calibration. Stochastic modeling, tracer tests, and geochemical data in the form of natural tracers can all be used to guide conduit locations in the model.

The hydrologic modeling should move toward making predictions on a daily time scale, e.g., by developing telescoping models of smaller regions. Unlike the monthly time step of the current modeling effort, a daily time step would better (1) address the ecological modeling needs, (2) account for the responsiveness of the aquifer, and (3) incorporate management scenarios that include 10-day running averages. While there are some data limitations and computational limitations to shortening the time step, these issues are not insurmountable and can be addressed using either MODFLOW or FEFLOW.

Telescoping models or grid refinement would be advantageous in the spring areas where the ecological targets are formulated. The finer time step and grid can also be used to incorporate heterogeneities and better evaluate recovery times for scenarios that stress the system. The regional models provide important boundary conditions, so both modeling efforts are needed and complement each other.

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3

Ecological Modeling

The major spring systems of the Edwards Aquifer are home to many plants and animals, including seven federally listed endangered species, one federally listed threatened species, and three vulnerable species for which petitions for addition to the endangered species list have been filed (see Chapter 1). There are many threats to the listed species, including loss of habitat from reduced spring flows, interactions with non-native species, habitat destruction or modification by humans (e.g., recreation, bank erosion), and other factors that degrade water quality. Three of the species covered by the Incidental Take Permit—the fountain darter, the Comal Springs riffle beetle, and Texas wild rice—are designated as indicator species, whose protection under the Habitat Conservation Plan (HCP) is assumed to ensure adequate protection for the other eight species. This chapter first discusses what is found in the HCP regarding the indicator species, in terms of the goals for each species and the habitat suitability analysis. Next, the chapter discusses the development of ecological models for fountain darter, submersed aquatic vegetation (SAV), and the Comal Springs riffle beetle, which are the only new ecological models that have been proposed to date. The chapter concludes with recommendations for improving these modeling efforts.

WHAT IS IN THE HABITAT CONSERVATION PLAN?

The HCP provides a baseline of information on the listed species that is to be built upon during the 15 years of HCP implementation, particularly during Phase I (the first seven years). Long-term biological goals are specified for the listed species, in terms of the desired density of individuals in key habitat types, desired habitat areal coverage, and critical water quality and quantity parameters that must be attained and maintained over the life of the HCP. It is not the purpose of this NRC report to critique the biological goals as they will be the subject of the third and final NRC report. However, they are presented here for all of the listed species to provide context.

In addition to the biological goals, the HCP outlines a biomonitoring program intended to gather data on the listed species that can then be used to ensure compliance with the biological goals in the HCP, assess the health of the communities, parameterize and test the ecological models, and gain greater understanding of species biology and ecology. Although the Committee's main critique of the biomonitoring program can be found in Chapter 4, the monitoring efforts for some species are mentioned here when critical to the ecological modeling efforts.

Finally, for all of the listed species, a spring flow objective has been assigned, below which the species are thought to be imperiled. The values used for spring flow objectives were

derived from habitat suitability analyses done for fountain darter, Texas wild rice, and Comal Springs riffle beetle (and appear as appendices to the HCP). Because these analyses represent the current state of ecological modeling for these species, a description and critique of the efforts are provided here. (Note that the Committee did not perform a comprehensive review of all possible ecological models for the indicator species, but rather focused on those recently used, currently in use, or planned.)

As described in Box 3-1, the habitat suitability analyses were all supported by two-dimensional hydrodynamic models that estimated the distribution of water depths and velocities as a function of simulated flow rate for specific sections of both the Comal and San Marcos Rivers. Temperatures were derived from simulations of the QUAL2E water quality model. These model outputs were used in combination with habitat suitability curves for water depth and velocity to estimate available habitat for Texas wild rice and the Comal Springs riffle beetle (CSRB) over a variety of flow rates. Fountain darter habitat was modeled using water depth, velocity, temperature, and vegetation type, with vegetation data being derived from historical vegetation maps.

Box 3-1
Hydrodynamic and Water Quality Modeling to Support the Habitat Suitability Analyses

The first habitat suitability analysis done for fountain darter, Texas wild rice, and Comal Springs riffle beetle (Hardy, 2009) relied on hydrodynamic models of the Comal and San Marcos rivers. To support the first habitat suitability analysis, two dimensional hydrological models of the rivers (RMA2 for the Comal system; FESWMS for the San Marcos system) were calibrated. Model results for dissolved oxygen and temperature from earlier QUAL2E studies were used. The model HEC-RAS (1-D) was used to generate water surface elevations, which served as boundary conditions for each river segment, and each segment was simulated separately. Vegetation was mapped to the 2-dimensional cells within each segment to determine roughness and velocities near the bottom. Water depths and velocities were predicted under steady-state conditions for each segment separately. Water temperatures under steady state conditions were simulated for the entire system rather than segment by segment. For the purpose of the first habitat suitability analysis, the Comal system was divided into 18 segments and the San Marcos system into 21 segments. Simulation results for Comal consisted of velocities, depth, and temperature for a series of constant spring flows (30, 60, 100, 150, 300 cfs) and specified alternative routing between the Old and New Channels. Simulations for San Marcos were similar, and generated depths, velocities, and temperature for a series of constant spring flows (15, 30, 65, 100, 135, 170, 190, and 200 cfs).

In a follow-up habitat suitability analysis (Hardy et al., 2010), the 2-D hydrological framework used in the first analysis was improved upon. The second analysis included habitat and temperature effects at spring flows observed during drought conditions. Topography and vegetation mapping were updated, and the model MDSWMS was used to simulate 2-dimensional hydraulics in separate segments in the riverine portions of each system. The Comal system was divided into 11 riverine segments and the San Marcos system into 12 riverine segments, both with 0.25 meter resolution. Calibration was done for each segment. The lakes in both systems were also simulated, with habitat in Spring Lake considered fixed and independent of spring flow and habitat in Landa Lake dependent on flow due to drying of some potential habitat areas. The QUAL2E model was re-calibrated for both systems to simulate temperature. The models were calibrated to 2009, and then used to simulate velocities, depths, and temperature for a series of fixed spring flows (30 to 260 cfs for San Marcos; 30 to 300 cfs for Comal).

Texas Wild Rice

Within the HCP there are biological goals, a habitat suitability analysis, and a description of biomonitoring in the San Marcos system, all for Texas wild rice. However, the HCP also places great importance on SAV because of its role in providing fountain darter habitat. Thus, the ecological model currently being developed is for SAV, with the goal of eventually coupling the SAV and fountain darter models to enable simulation of spatially and temporally varying habitat within the fountain darter ecological model. There is also the possibility that the SAV model might be modified in the future to encompass Texas wild rice (i.e., to predict Texas wild rice responses to variation in flows and other environmental conditions). The sections below focus only on Texas wild rice, while the section on ecological modeling later in the chapter focuses exclusively on SAV.

HCP Goals and Objectives for Texas Wild Rice

The long-term biological goals for Texas wild rice are based on maintenance of areal coverage in four segments of the San Marcos River. According to the HCP, the actual long-term goals (Table 3-1) are based on an evaluation of (1) the maximum occupied area of Texas wild rice that has been present in the San Marcos system over time; (2) Texas Parks and Wildlife Department analysis of the Hardy et al. (2010) physical habitat modeling; and (3) the 1996 U.S. Fish and Wildlife Service (FWS) recovery plan goals (USFWS, 1996; EARIP, 2012, Section 4.1.1.2).

TABLE 3-1 Long-term biological goal for Texas wild rice in four segments of the San Marcos River.

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 IH-35	910 – 1,650	13 – 12
Downstream of IH-35	280 – 3,055	4 – 22
TOTAL	8,000-15,450	100

SOURCE: EARIP, 2012, Table 4-10

Three management objectives have been formulated with respect to the long-term goals for Texas wild rice: a minimum areal coverage during the drought of record, recreational awareness, and restoration and expansion efforts. The minimum areal coverage objectives have been formulated separately for each of the river segments (Table 3-2).

TABLE 3-2 Minimum Texas wild rice areal coverage per segment during drought of record-like conditions.

River Segment	Areal Coverage (m^2)	Reach Percentage of Total Areal Coverage
Spring Lake	500	n/a
Spring Lake Dam to Rio Vista Dam	2,490	83
Rio Vista Dam to IH-35	390	13
Downstream of IH-35	120	4
TOTAL	3,550	100

SOURCE: EARIP, 2012, Table 4-11

A major concern regarding Texas wild rice is recreational activity in high-quality habitat areas of the San Marcos River, including swimming, snorkeling, scuba, non-motorized boating, tubing, wading, fishing, and recreating with dogs. Although the exact impacts of these recreational activities on Texas wild rice are unknown, a greater percentage of plants are exposed to potential negative consequences as discharge decreases. Damage to Texas wild rice stands by recreationists, particularly dogs, through direct contact has been documented (EARIP, 2012, pp.4-42). Texas wild rice is further impacted through fragmentation of other vegetation that then floats downstream eventually collecting on Texas wild rice stands. While there are hard-scaped access points in all adjacent city parks, numerous ad hoc access trails created by recreationists contribute to bank erosion. The HCP targets the entire San Marcos River for recreation awareness, and four segments within three reaches have been identified as targets for recreation control when flows decline below 100 cfs.

Recreation control during low-flow conditions within key high quality habitat areas for Texas wild rice is viewed as necessary in order to limit unnecessary impacts, rather than general recreation restriction for large parts of the river. Therefore the City of San Marcos plans to establish five or more permanent river access points to allow public access while attempting to limit potential damage. Areas between these access points will be planted with vegetation to discourage streamside access. The Texas Parks and Wildlife Department (TPWD) will further restrict access along select shoreline areas during low flow conditions by establishment of State Scientific Areas. The City of San Marcos will construct kiosks at key locations to provide information to the public detailing access points, protected or restricted areas, and other educational information.

Active restoration and Texas wild rice expansion efforts are to be focused primarily on high-quality habitat areas. The City of San Marcos and Texas State University will implement a Texas wild rice enhancement and restoration program. Areas that have a high probability of success based on the Hardy et al. (2010) habitat suitability analysis will be targeted for Texas wild rice restoration and habitat enhancement.

In addition to the habitat-based long-term biological goals and the associated restoration and water quality management objectives, the HCP also identifies flow-related objectives for Texas wild rice (Table 3-3).

TABLE 3-3 Long-term average and minimum total San Marcos Spring discharge management objectives. These apply not only to Texas wild rice but also to fountain darter and other species.

Description	Total San Marcos Discharge (cfs)[a]	Time-step
Long-term average	140	Daily average
Minimum	45[b]	Daily average

[a]Assumes a minimum of a 50-year modeling period that includes the drought of record
[b]Not to exceed six months in duration followed by 80 cfs (daily average) flows for 3 months.
SOURCE: EARIP, 2012, Table 4-13.

Habitat Suitability Analysis for Texas Wild Rice

Over the last 15 years, there have been several efforts to determine habitat suitability criteria for Texas wild rice (Bartsch et al., 2000; Hardy, 2009; Hardy et al., 2010). Factors such as water depth, substrate type, water velocity, canopy cover, and the concentrations of inorganic compounds including dissolved oxygen were considered to influence Texas wild rice populations. The most relevant habitat suitability curves have been found to be those based on water depth and velocity, and most habitat suitability analyses for Texas wild rice have focused only on those two parameters. Texas wild rice data collected by the Texas Parks and Wildlife Department and by the FWS were used to generate very similar habitat suitability criteria, showing that the most suitable water depths for Texas wild rice range from about 1 to 3 feet, and the most suitable water velocities range from about 0.5 to 2 ft/sec (Hardy, 2009, Figures 26-27). Values for suitability, based on single or multiple parameters, vary from 0 to 1.

Habitat suitability criteria for water depth and velocity were used in the following equation to determine overall habitat suitability for Texas wild rice in various sections of the San Marcos River (Hardy, 2009):

$$\text{Overall suitability} = \text{depth suitability} \times \text{velocity suitability}$$

where depth suitability and velocity suitability are determined by taking their respective values for the hydraulic simulation results at a node and using linear interpolation between the defined suitability values from the habitat suitability index curves. The suitability value determined for a computational cell is then multiplied by the cell area, generating a Weighted Usable Area for that cell. At a given simulated discharge, all Weighted Usable Area values are summed within a specific computational reach to generate a total quality-weighted area at the reach level.

Hardy (2009) provided results from multiple different habitat suitability analyses for Texas wild rice. Some of the later analyses benefitted from more precise physical modeling of the river system or from more recent data sets. Nonetheless, all of the analyses show the same basic trends, which are that the most suitable habitat for Texas wild rice seems to peaks around 150 cfs, and that suitable habitat begins to drop below discharge rates of 100 cfs and drastically drops below 65 cfs (Hardy, 2009, Figure 45). Observed Texas wild rice data superimposed on the model predictions for areas of suitable habitat provided some support for the model's ability to identify high and low quality habitat (see Figure 3-1). Many of the observed locations of Texas wild rice were in or near cells that were predicted to be high quality. Furthermore, the model predicted little to no Texas wild rice habitat in Spring Lake, which is expected because there is no flow in the lake above the threshold for Texas wild rice. Similarly, in the lower San

Marcos River, the model predicted poor habitat because of deep water, which agrees with the lack of Texas wild rice in that area.

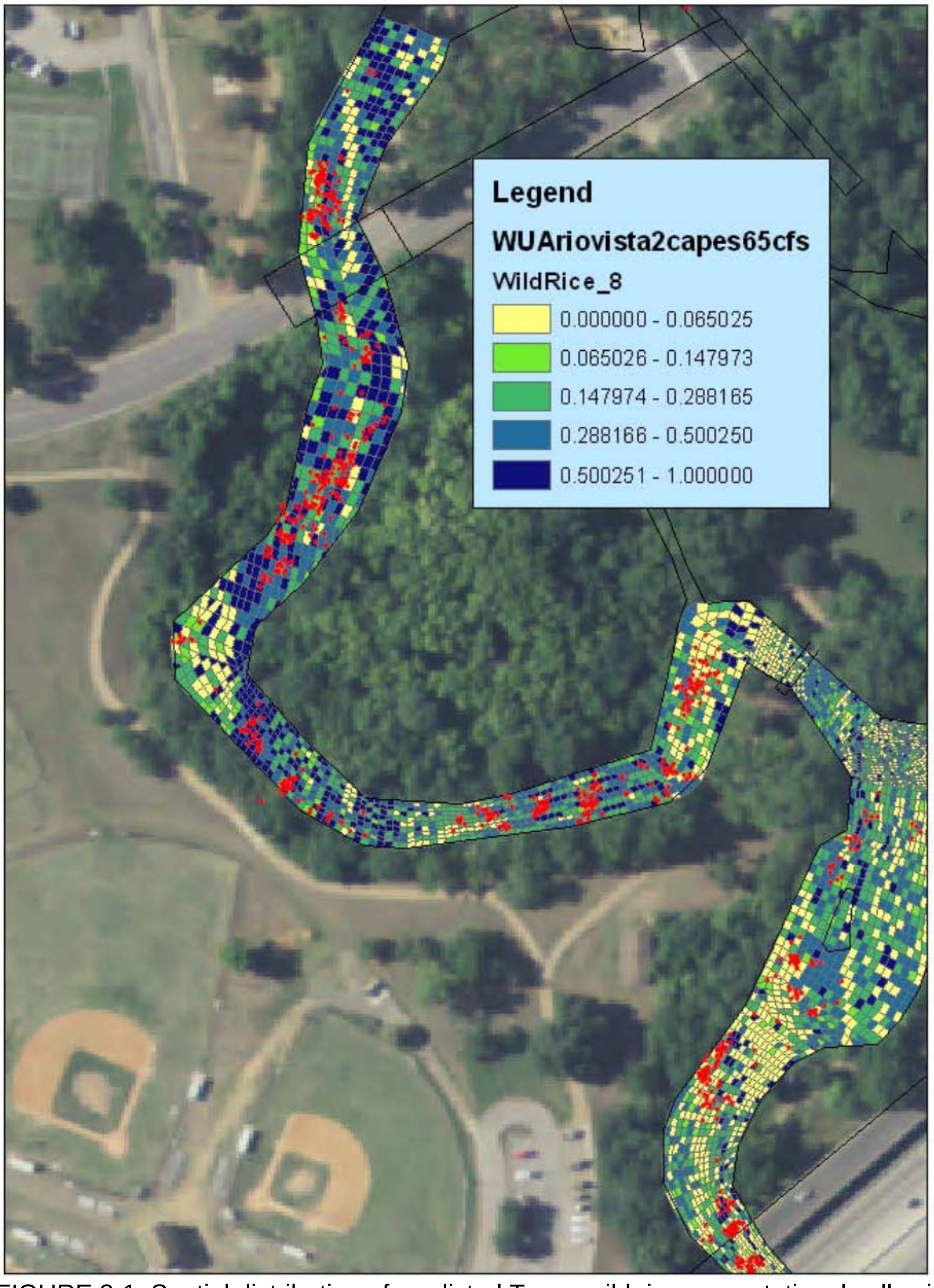

FIGURE 3-1 Spatial distribution of predicted Texas wild rice computational cell suitability ranges versus the 1989 to 2008 spatial distribution of Texas wild rice stands (red dots) in the Rio Vista to Cape's Dam section. Simulated discharge is 65 cfs.
SOURCE: Hardy (2009).

Several improvements were made in a subsequent habitat suitability analysis (Hardy et al., 2010). The two-dimensional hydrodynamic models and the QUAL2E models of the river systems were updated, and habitat criteria for Texas wild rice were updated based on more recent monitoring data (see Figure 3-2). Vegetation mapping was conducted in both river systems and integrated into the hydraulic modeling as spatially explicit roughness and in the habitat modeling as vegetation composition. The 2009 Texas wild rice monitoring data collected the Texas Parks and Wildlife Department and U.S. Fish and Wildlife Service were combined with current vegetation maps.

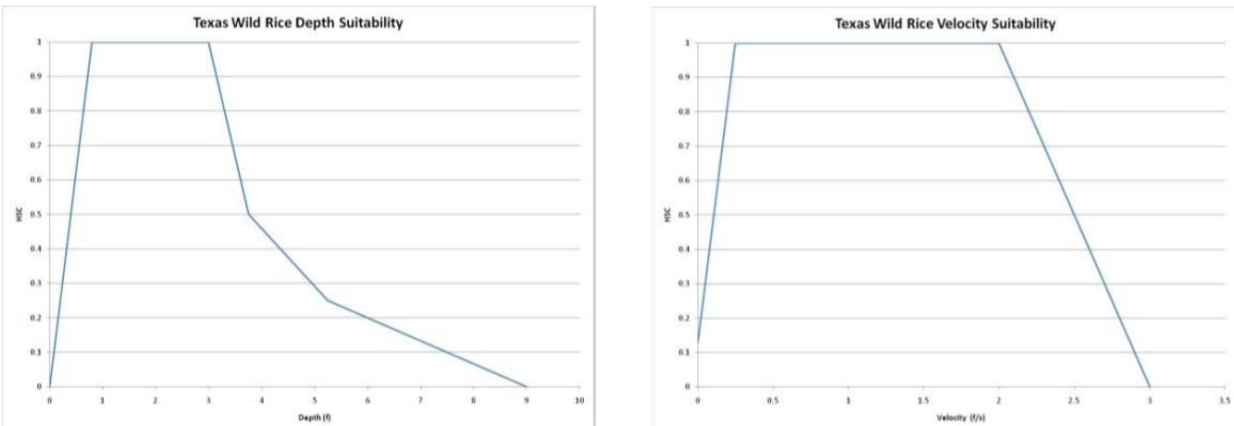

FIGURE 3-2 Updated Habitat Suitability Curves (HSC) for Water Depth (left) and Velocity (right) used in the Hardy et al. (2010) analysis.
SOURCE: Hardy et al. (2010).

The modeling approach was similar to previous analyses, in that depth and velocity were the two main controlling factors for determining habitat suitability for Texas wild rice, but the two factors were combined as a geometric mean rather than as a simple product:

$$\text{Combined Suitability} = (\text{depth suitability x velocity suitability})^{1/2}$$

The model was run for various fixed spring flows ranging from 30 cfs to 260 cfs. As expected, optimal habitat for Texas wild rice increased as discharge increased, until habitat began slowly decreasing as flows exceeded 150 cfs. Because low flows (30-80 cfs) are the focus of the HCP, and because the model predicted little variation in the optimal amount of habitat for Texas wild rice at such flows (see Figure 3-3), Hardy et al. (2010) concluded that *"…the proposed flow regime within the San Marcos River being considered by the EARIP will provide adequate quantity and quality habitat to sustain this species during similar instances as the drought of record* ***provided*** *effective recreation control can be implemented."*

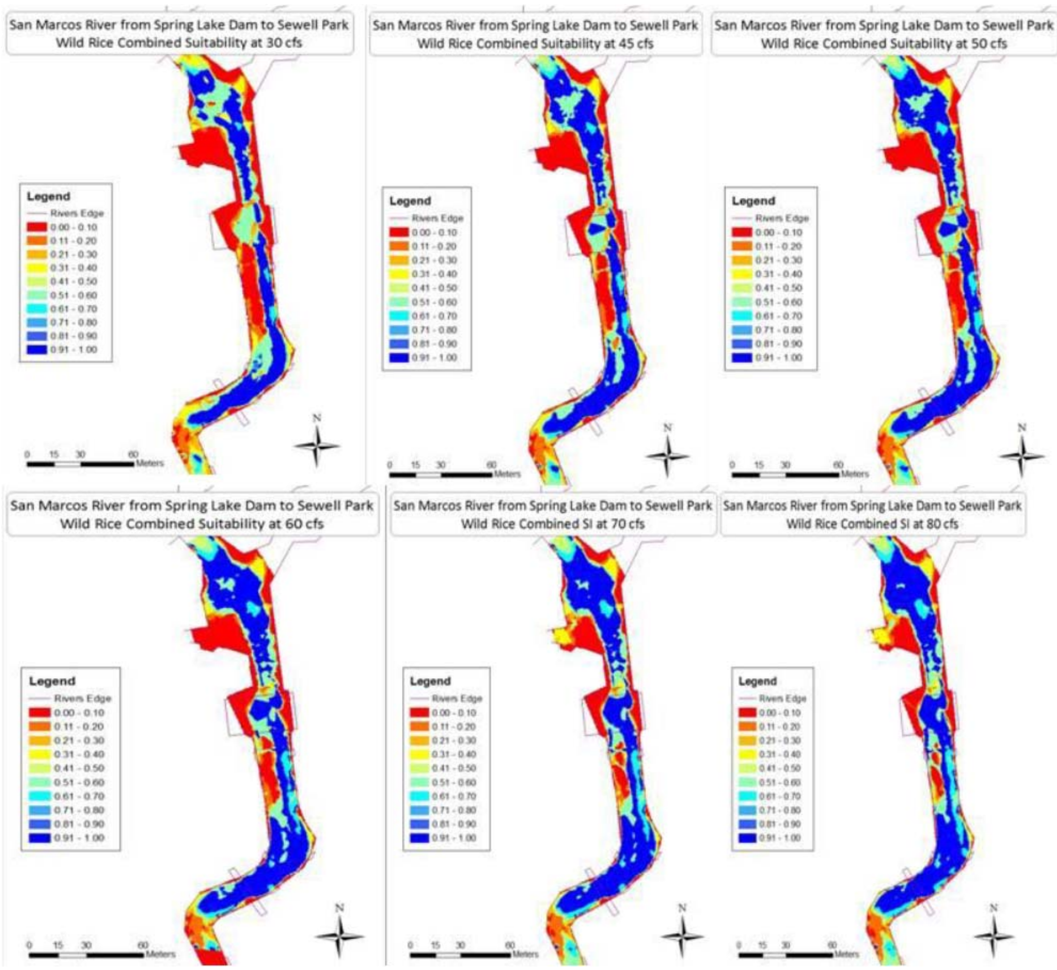

FIGURE 3-3 Combined suitability for TWR physical habitat for a range of discharge (30-80 CFS) within the Saltgrass to Sewell Park reach of the San Marcos River.
SOURCE: Hardy et al. (2010), Figure 29.

Interestingly, Texas wild rice currently occupies only a small percentage of its optimal habitat as defined by depth and velocity (see Figure 3-1; Hardy et al., 2010). There could be many reasons: non-optimal discharge, competition with other plant species, human disturbance, poor water quality, and other factors that limit Texas wild rice survival in these areas. There are about 2,600 m^2 of Texas wild rice in the entire San Marcos River, but there could be well over 35,000 m^2 if the discharge was optimal and assuming only depth and velocity determined habitat quality. The Hardy et al. (2010) report mentions the possibility of expansion of Texas wild rice into areas that are optimal but not currently occupied by Texas wild rice as well as a 2-m buffer around existing stands.

Currently, the habitat suitability analysis is the only ecological model for Texas wild rice. Given the lack of plans for a more rigorous Texas wild rice ecological model, the Committee recommends continuing and improving upon the habitat suitability effort. The goal would be to better account for the areas predicted to be suitable habitat that, in fact, do not support Texas wild rice. That is, failure of Texas wild rice to establish in an area determined to be optimal based on the habitat suitability analysis could point to other important driving variables like

competition from non-native species (see Chapter 1 page 18), recreation, and other human activities. It would also be useful to update the analyses to include the effects of restoration efforts for Texas wild rice. Specifically, it would be beneficial to quantify all recreation exclusion, replanting, and other minimization and mitigation activities, particularly as they relate to the assumed optimal habitat. As discussed in Chapter 5, such information could be gathered from targeted Applied Research projects. In general, data on the distribution of Texas wild rice could be used annually to help validate the Habitat Suitability analysis, which would also be improved by the inclusion of error estimation (e.g., in the hydrodynamics model).

Fountain Darter

HCP Goals and Objectives for Fountain Darter

The long-term biological goals for the fountain darter are based on maintenance of preferred fountain darter habitat. Four representative reaches in Comal system (Upper Spring Run, Landa Lake, Old Channel, and New Channel), and three representative reaches in the San Marcos system (the Spring Lake Dam, City Park, and I-35 Reaches) (Figure 3-4) have been identified for achieving the goals. The goals consist of maintaining the areal coverage of aquatic macrophytes and algae, and the densities of fountain darters, at or above the median values observed for each during the decade-long EAA Variable Flow Study (BIO-WEST, 2007; see Table 3-4). The approach to determining the vegetation areal targets was to use the spring and fall vegetation mapping in each representative reach and to couple the areal targets with defined darter densities (median values observed in the study) by vegetation type. Achieving both would then confirm that both habitat and darters were at their targeted values (habitat area and number of fountain darters per area).

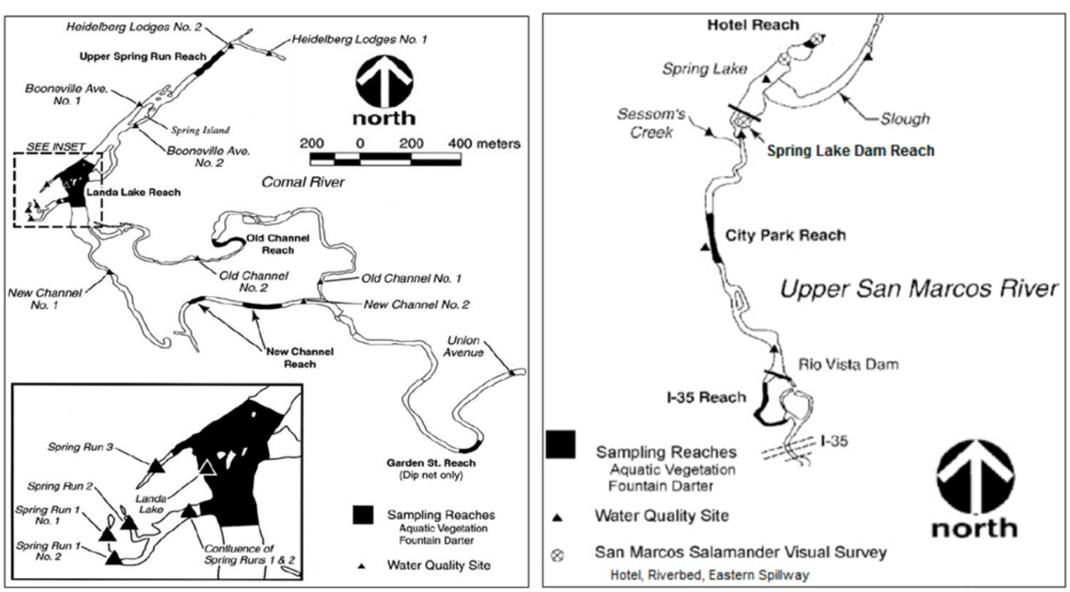

FIGURE 3-4 Schematics showing representative reaches for Comal (left) and San Marcos (right) spring systems to be used in monitoring for fountain darter habitat and population densities. SOURCE: EARIP (2012).

TABLE 3-4 Goals for fountain darter habitat (aquatic vegetation areal coverage, m^2) and fountain darter density (number/m^2) for each habitat type in Comal and San Marcos Springs.

COMAL SPRINGS							
Coverage (m^2)	Bryophytes	*Hygrophila*	*Ludwigia*	*Cabomba*	Fil. Algae	*Sagittaria*	*Vallisneria*
Upper Spring Run	1,850	650	150	0	0	600	0
Landa Lake	4,000	250	900	500	0	1,250	13,500
Old Channel	150	200	1500	0	300	0	0
New Channel	150	1,350	0	350	0	0	0
Fountain darter (no./m^2)	20	4	7	7	14	1	1

SAN MARCOS SPRINGS							
Coverage (m^2)	*Hygrophila*	*Ludwigia*	*Cabomba*	*Hydrilla*	*Potamogeton*	*Sagittaria*	*Vallisneria*
Spring Lake Dam	50	200	25	100	1,000	100	125
City Park	200	1,000	50	500	2,000	300	50
I-35	50	200	300	100	300	100	25
Fountain darter (no./m^2)	4	7	7	5	5	1	1

SOURCE: EARIP (2012).

The HCP does not state what actions will be taken if measured darter densities fall below the median density goals in certain vegetation types in certain reaches, nor is there any discussion of variability in the median values of darter densities.

The EAA has formulated two management objectives for achieving the fountain darter long-term goals: (1) restoration and protection of native vegetation and (2) maintenance of historical water quality. The native vegetation (also considered the preferred habitat of fountain darters) will be protected, and restored when damaged, to maintain species-specific areal coverages at or above the values shown in Table 3-4. Surface water quality will be maintained within a 10 percent deviation of all monitored parameters, except temperature and dissolved oxygen, from the average recorded water quality measured at 15 locations during the EAA Variable Flow Study. This water quality objective is based on the assumption that a 10 percent deviation in average conditions would be suitable for the darters; however, more extensive work to assess water quality tolerances of fountain darters will be addressed as part of the HCP. Water temperatures less than 25°C and dissolved oxygen concentrations greater than 4.0 mg/L will be maintained to ensure fountain darter survival, reproduction, and recruitment.

As with Texas wild rice, along with the habitat-based long-term biological goals and the associated restoration and water quality management objectives, the HCP also identifies flow-related objectives to help ensure maintenance of fountain darter populations (see Table 3-5).

TABLE 3-5 Long-term average and minimum total discharge management objectives for Comal and San Marcos Springs.

Description	Total Comal Spring Discharge (cfs)	Total San Marcos Spring Discharge (cfs)	Time-step
Long-term average[a]	225	140	Daily average
Minimum[b]	30	45	Daily average

[a]Assumes a minimum of a 50-year modeling period that includes the drought of record
[b]Not to exceed six months in duration followed by 80 cfs (daily average) flows for 3 months.
SOURCE: EARIP (2012).

Habitat Suitability Analysis for Fountain Darter

Three habitat suitability analyses were performed for fountain darter, described very briefly below; the reader is referred to the original reports for more information. The first two analyses (Hardy, 2009; Hardy et al., 2010) used the output of hydrologic and temperature models that predicted depth, velocity, and water temperature in computational grid cells within segments of each of the two systems (see Box 3-1). The first report (Hardy, 2009) related fountain darter habitat suitability to vegetation type, depth, velocity, and temperature. The second Hardy analysis (2010) was similar but used updated hydrologic models, dynamic temperature simulations, and revised suitability functions. The third habitat analysis only appeared in the HCP itself and used a habitat-based approach that was different from the two Hardy analyses. The HCP analysis was done for each of the representative reaches only, and used the area of the dominant vegetation, adjusted for spring flow, multiplied by assumed darter densities by vegetation type, also adjusted for spring flow, to determine darter abundances by representative reach every six months for nine years during the EAA Variable Flow Study.

Hardy (2009). In the first analysis, habitat suitability was computed as the product of the individual suitabilities for depth, velocity (water column or 0.5 feet off the bottom), vegetation type, and temperature (daily average or maximum). The curves were determined by examination of field data coupled with expert opinion. Dissolved oxygen simulations were considered questionable because sediment oxygen demand and plant respiration were not explicitly included in the model.

As for the Texas wild rice analysis, the predicted weighted usable areas by region (groups of segments) were plotted across the assumed constant spring flows for both the Comal and San Marcos systems. A second constant flow analysis done for Comal used more spring flows and New/Old Channel splits, focused in the lower segments only, and used maximum daily temperature rather than averaged daily temperature. The weighted usable areas reported for old results (e.g., Bartsch et al., 2000) were compared to new results for the Comal and San Marcos systems that used revised channel geometries and habitat suitability curves.

Hardy et al. (2010). In the newer Hardy analysis, the updated hydraulic and QUAL2E models were combined with the geometric means of new habitat suitability curves for depth, velocity, and vegetation type (but not temperature) to determine weighted useable areas for fountain darter. Two of the habitat suitability curves are shown in Figure 3-5, which imply that

habitat quality for fountain darter increases with depth, and it decreases as velocity exceeds 0.5 ft/sec. Habitat suitability for each vegetation and substrate type is given in Table 3-6.

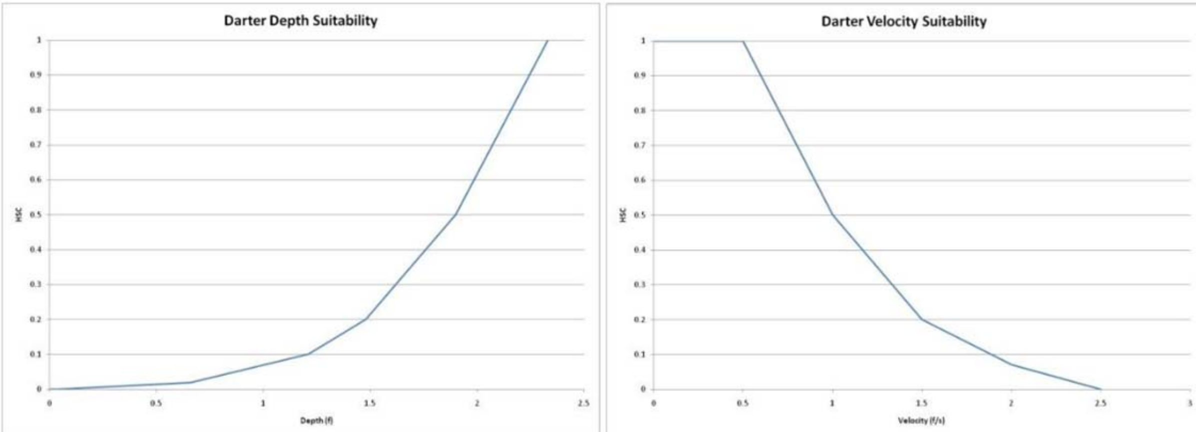

FIGURE 3-5 Habitat suitability curves for fountain darter as a function of water depth (left) and water velocity (right).
SOURCE: Hardy et al. (2010).

TABLE 3-6 Habitat Suitability of Fountain Darter by Vegetation and Substrate Type

Vegetation/Substrate classification	Code	HSI Value	Vegetation/Substrate classification	Code	HSI Value
Clay	1	0.05	*Acmella oppositifolia*	27	0.25
Silt	2	0.05	*Arundo donax*	28	0.05
Sand	3	0.05	*Ceratopteris thalictroides* 75-100%	29	0.06
Gravel	4	0.05	*Ceratopteris thalictroides* 50-75%	29.1	0.06
Cobble	5	0.10	*Echinochloa sp*	30	0.05
Small Boulder	6	0.05	*Heteranthera dubia* 75-100%	31	0.80
Large Boulder	7	0.05	*Heteranthera dubia* 50-75%	31.1	0.80
Bedrock	8	0.05	*Hydrocotyle sp* 75-100%	32	0.20
Large Woody Debris	9	0.05	*Hydrocotyle sp* 50-75%	32.1	0.20
Concrete	10	0.05	*Juncus texanus* 75-100%	33	0.05
Artificial Wood	11	0.05	*Juncus texanus* 50-75%	33.1	0.05
Metal	12	0.05	*Justicia americana* 75-100%	34	0.00
Hydrilla verticillata 75-100% cover	13	0.29	*Justicia americana* 50-75%	34.1	0.00
Hydrilla verticillata 50-75% cover	13.1	0.29	*Iris pseudocoris*	35	0.60
Hygrophila polysperma 75-100% cover	14	0.93	*Ludwigia sp* 75-100%	36	0.56
Hygrophila polysperma 50-75% cover	14.1	0.93	*Ludwigia sp* 50-75%	36.1	0.56
Colocasia esculenta 75-100% cover	15	0.60	*Myriophyllum sp* 75-100%	37	0.80
Colocasia esculenta 50-75% cover	15.1	0.60	*Myriophyllum sp* 50-75%	37.1	0.80
Potamogeton illinoensis 75-100%	16	0.01	*Nasturtium officinale* 75-100%	38	0.00
Potamogeton illinoensis 50-75%	16.1	0.11	*Nasturtium officinale* 50-75%	38.1	0.00
Zizania texana 75-100%	17	0.11	*Nuphar advena*	39	0.20
Zizania texana 50-75%	17.1	0.11	*Nuphar advena*	39.1	0.20
Zizania texana <50% mono with substrate	17.2	0.11	*Ricinus*	40	1.00
Sagittaria platyphylla 75-100%	18	0.16	*Typha lattifolia*	41	0.60
Sagittaria platyphylla 50-75%	18.1	0.16	*Utricularia gibba*	42	0.00
Cabomba caroliniana 75-100%	19	0.54	*Vallisneria americana* 75-100%	43	0.13
Cabomba caroliniana 50-75%	19.1	0.54	*Vallisneria americana* 50-75%	43.1	0.13
Ceratophyllum demersum 75-100%	20	0.02	*Xanthosoma sagittifollium*	44	0.01
Ceratophyllum demersum 50-75%	20.1	0.02	*Cynodon dactylon*	45	0.05
Submergent Vegetation Mix	21	0.50	*Salix nigra*	46	0.05
Emergent Vegetation Mix	22	0.20	*Limnophila sessiflora*	47	0.20
Submergent/Emergent vegetation mix	23	0.25	*Chara sp*	48	1.00
Floating vegetation	24	0.00	Algae	49	1.00
Floating/Submergent vegetation mix	25	0.25	*Zizianopsis*	50	0.11
Unclassified	26	0.50	Moss	51	0.50

SOURCE: Hardy et al. (2010).

The weighted useable area based on physical habitat was computed for the series of fixed spring flows for each system. Weighted useable area increased steadily with increasing spring discharge for the San Marcos system (see Figure 3-6), while it showed a sharp increase between about 10 and 30 cfs in the Comal system (Figure 3-7).

Once weighted useable areas were computed, the effects of temperature were factored in, keeping in mind three critical temperatures for fountain darter: lethality at 94.6 F, reproduction ceasing above 86 F, and increased larval mortality starting at 78.8 F (Hardy et al., 2010). For San Marcos, thermal limitations were most apparent at flows below 45 cfs, although Spring Lake would remain cool. Hardy et al. (2010) concluded that darter reproduction and larval survival would be sufficient above 45 cfs in the San Marcos system. In the Comal system, significant temperature limitations were noted below 30 cfs, but generally not above 80 cfs. [Not all of the report conclusions are included here; details can be found in Hardy (2009) and Hardy et al. (2010)].

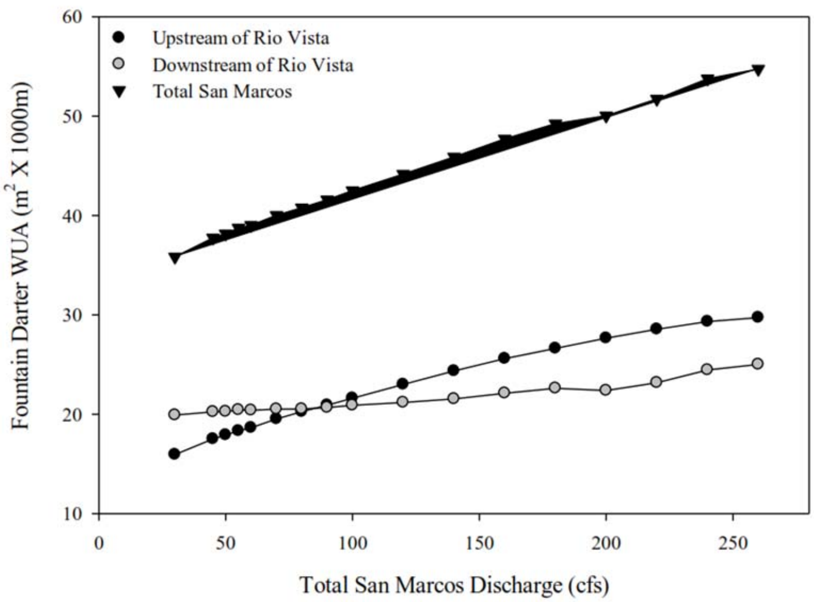

FIGURE 3-6 Relationship between the amount of fountain darter Weighted Usuable Area (m^2 x 1000) upstream of Rio Vista (black dots), downstream of Rio Vista (gray dots), and total San Marcos River under various discharges.
SOURCE: Figure 40 from Hardy et al. (2010).

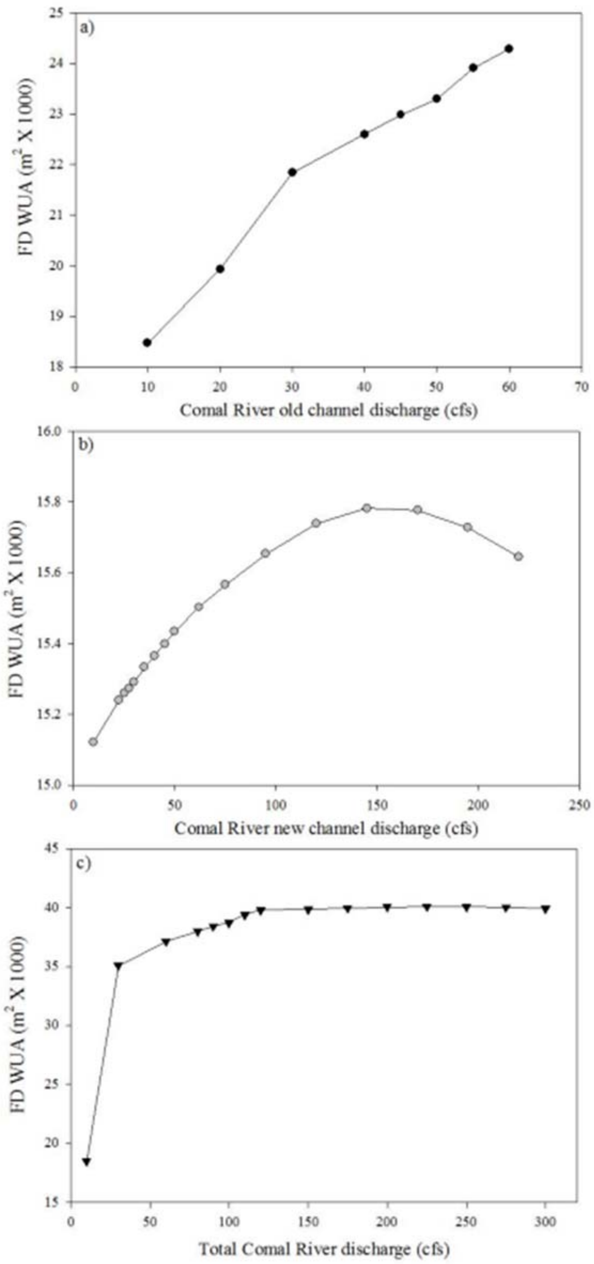

FIGURE 3-7. Weighted usable area (WUA) for fountain darter at various discharges within the Comal River.
SOURCE: Figure 48 in Hardy et al. (2010).

HCP Habitat Analysis. A third habitat suitability analysis appeared in the HCP, which was labelled as a population model, although it does not meet the standard definition of such a model. This analysis used the predictions of spring flow generated by the MODFLOW model to determine fountain darter abundance under five scenarios: (1) no-action, where the HCP is not implemented (pumping of 527,000 ac-ft), (2) the existing baseline (pumping of 381,000 ac-ft), (3) the historical data (actual monthly flows), (4) implementation of the HCP-Phase 1, and (5) implementation of the HCP-Phase 2.

Unlike the Hardy efforts, habitat suitability in this analysis was related only to spring flows and vegetation type. First, a suitability function was defined for each vegetation type as a function of flow. Second, darter densities by vegetation type were estimated, and a habitat quality ranking (1–4) was defined that dictated which density value was used for that vegetation type. (A ranking of one means use the minimum density; a ranking of 3 means use the median density.) The goal of the analysis was to predict fountain darter densities and total darter abundance rather than a weighted useable area (as was done in Hardy, 2009, and Hardy et al., 2010). The results of the analysis are presented in tables of darter abundance summed over the representative reaches. The results were also extrapolated to the entire river system, plotted as time series values, and interpreted as to whether the population would be extirpated or not. This third suitability analysis was not based upon standard and easily defensible methods and is not likely to be as useful as a predictive tool.

The first habitat analysis of fountain darter (Hardy, 2009) was admittedly pieced together from new and existing modeling results—issues that were mostly addressed in the second Hardy et al. (2010) habitat analysis. The models in the second analysis were standardized between systems and recalibrated, and the suitability functions were updated. While temperature was included as part of the first suitability analysis, temperature was treated separately, and in a less quantitative way, in the second analysis.

The HCP repeatedly refers to the two Hardy habitat suitability analyses with statements that are not easy to trace back to the reports. The first habitat suitability analysis was included as Appendix H of the HCP, while the 2010 analysis was well-documented in a separate report and was referred to repeatedly in the main text of the HCP. An example of a statement that the Committee was unable to find supporting analyses for was “A review of the Hardy (2010) fountain darter modeling shows that there would be sufficient quality and quantity of habitat in all four reaches at long-term average flows (i.e., 225 cfs) to support the long-term biological goals for the fountain darter in the Comal system” (p. 4-9, EARIP, 2012).

The HCP’s apparent reliance on the third habitat suitability analysis to assess the effects of various spring flow scenarios on fountain darter abundances is questionable because of methodological and interpretation issues. The third analysis would require major modification before it could be used further. Some of the underlying calculations are valid and useful, but the couching of the analysis as a population model and showing time series of predicted abundances connected together with lines (e.g., Figures 4-31 and 4-32 in EARIP, 2012) is wrong and can easily lead to misinterpretation of the results. Little or no justification was provided for the derivations of the vegetation suitabilities related to flow or for the assignment of rankings to use certain fountain darter densities.

One aspect of the habitat modeling that could be revisited is the estimation of the fountain darter suitability curves. Much has been done recently with statistically based fitting of suitability curves (e.g., Feyrer et al., 2011; Johnson et al., 2013; Knudby et al., 2010; Zorn et al., 2012), partially as a result of the interest in predicting climate change effects on habitat and development of new statistical methods. With the availability of the monitoring data and other information, a more formal estimation of the habitat suitability curves is warranted.

Comal Springs Riffle Beetle

HCP Goals and Objectives for CSRB

The long-term biological goals for the Comal Springs riffle beetle (CSRB) are maintenance of suitable silt-free habitat conditions and beetle population densities in representative reaches of Comal Springs (Spring Run 3, Western shoreline, and Spring Island area). According to the HCP, silt-free habitat conditions will be maintained through continued spring flow at or above 30 CFS, protection of riparian vegetation in the areas adjacent to spring openings, and regulation of recreational activities throughout each of the three sample reaches. The CSRB population measurement goal is to maintain beetle densities greater than or equal to the median densities observed over the past six years of the EAA Variable Flow Study (i.e., ≥20 beetles per lure at Spring Run #3 and ≥15 beetles/lure on the Western shoreline of Landa Lake and in the Spring Island area).

There are two management objectives designed for achieving the long-term goals for the CSRB. Silt-free habitat conditions will be maintained by protection and restoration of riparian vegetation in the areas adjacent to spring openings, particularly Spring Run 3 and Western Shoreline reaches, and regulation of recreational activities throughout each of the three sample reaches. The second management objective pertains to water quality and is the same as that for fountain darter.

As with previously discussed species, to accompany the habitat-based biological goals and management objectives the HCP also specifies flow-related objectives (see Table 3-5), and it plans for further research to assess the CRSB's water quality tolerances.

Unlike for fountain darter habitat, it is more complex to quantify the amount (or areal coverage) of high quality habitat for the CSRB, and measuring population densities has been a challenge. Major unknowns of the CSRB include any meaningful understanding of their life history, their true distribution, and their use of subsurface habitat. Because of this lack of information, the habitat-based component of this goal simply involves maintaining silt-free substrates (gravels and cobbles) at 90 percent or more of the area throughout the representative sample reaches.

Due to the paucity of data for CRSB in the San Marcos system, it is not possible to establish specific long-term habitat-based biological goals. As such, the HCP assumes that the flow-related goals presented in Table 3-5 would be protective of this species, until such time as additional information becomes available. The HCP argues that this is a reasonable assumption because the CSRB inhabits similar areas to the San Marcos salamander and has similar habitat requirements, such that protection of the salamander and its habitat coupled with water quality protection of the aquifer should similarly protect CSRB. However, it is presently unknown to what extent these species actually overlap in the San Marcos system, as there has not been a quantitative study to determine the degree and variability in each species' range.

The HCP considers the CSRB to be an indicator species whose protection could potentially cover other threatened or endangered species (see EARIP, 2012, pg. 4-38). Biological goals for these other species are described in Box 3-2. To date there are no empirical

data available that can provide an objective assessment of how well the habitat requirements and population changes of the CSRB adequately represent these others species.

Box 3-2
Biological Goals for Other Covered Species

Comal Springs Dryopid Beetle and Peck's Cave Amphipod

The subterranean nature and restricted range of the Comal Springs dryopid beetle (to the headwaters of Comal springs and spring upwelling areas) suggests that it does not require substantial surface discharge from springs to survive. The HCP assumes that spring flow (of sufficient water quality) that continually covers spring orifices should prevent long-term damage to the population (EARIP, 2012). Similarly, the Peck's cave amphipod requirements include sufficient spring flow covering the spring orifices and adequate water quality to prevent long-term adverse impacts to the species. Also, like with other species, the HCP calls for more work within the Adaptive Management Program to assess water quality tolerances of these species.

San Marcos Salamander

The long-term biological goals for this species are based on both qualitative habitat and a quantitative population components and employs a representative reach approach similar to that of the CSRB. The population goal is to maintain equal or greater densities than the median observed density over the past ten years of monitoring. Two management objectives are "aquatic gardening" (i.e., use of a harvester boat and hand cutting of vegetation by divers in the Riverbed area of Spring Lake) and recreational control similar to that used for Texas wild rice. These are to establish permanent access points along the banks of the San Marcos River and other areas as determined during the AMP, in addition to establishing TPWD State Scientific Areas.

Texas Blind Salamander

The HCP long-term biological goal for Texas blind salamanders is based only on water quality, with the same management objective as for the CSRB and other species (i.e., 10 percent deviation from historically recorded water quality), as well as a need for further research. Nevertheless, the HCP stipulates that previously discussed flow-related objectives are likely amenable to survival of this species.

Edwards Aquifer Diving Beetle, Comal Springs Salamander, and Texas Troglobitic Water Slater

These species are not presently on the federal endangered and threatened species list, but petitions have been filed. There are no explicit goals and objectives for these species in the HCP.

Habitat Suitability Analysis for CSRB

Hardy (2009) presents a habitat suitability analysis for the CRSB, with suitability being a function of water depth and velocity. This was followed by an updated analysis in Hardy et al. (2010). It is difficult to understand what information was actually used to determine the suitable habitat of the CSRB. For example, p. 36 of Hardy (2009) states: "Usual water depth in occupied habitat is 2 to 10 cm (1 to 4 inches) although the beetle may also occur in slightly deeper areas within the spring runs." Yet there is no additional information given on these slightly deeper habitats in terms of their potential areal extent, and these areas of additional habitat are ignored

from the equation used to model habitat. Other attempts to support the rationale for modeling CRSB habitat included a "modified random sampling technique" that indicated that the CSRB was restricted to the main spring runs at depths of up to 2.0 ft (0.61 m) and velocities of up to 2.0 ft/sec. In the final analysis, the suitable physical habitat of the CSRB was estimated simply as the total surface area of the main spring runs (Springs 1, 2 and 3) of Landa Lake where water depths were less than 0.02 feet (Hardy, 2009, p. 45).

Although this approach is conservative, it could underestimate the amount of suitable CSRB habitat, given that the beetle has been reported from additional major springs and spring orifices along the margins of and within Landa Lake (unfortunately depths have not been consistently reported). Interestingly, Hardy et al. (2010) discusses the fact that the main springs of Landa Lake ceased to flow for about five months in the early 1950s, but that CSRB populations were detected after flow resumed in these habitats, indicating that the populations in these springs can become reestablished after months of surface drying.

Given the limitations associated with sampling this species (see Chapter 4), it is not currently possible to model the true habitat availability or the occupied portion of the total available habitat. Until more quantitative sampling methods are developed and more is known about the beetle's life history it will be difficult to model CSRB population or its preferred habitat and how these change in response to flow or sedimentation. Chapters 4 and 5 provide more detailed recommendations on how to improve these aspects of understanding CSRB.

DEVELOPMENT OF ECOLOGICAL MODELS FOR SUBMERSED AQUATIC VEGETATION, FOUNTAIN DARTER, AND COMAL SPRINGS RIFFLE BEETLE

A major activity of the HCP is the development of predictive ecological models for indicator species in the Comal and San Marcos Spring systems. The rationale given for the creation of these models is to be able "to investigate potential impacts to these ecosystems from extreme short-term and sustained long-term impacts from natural and anthropogenic factors, including local and regional groundwater withdrawals." Although the HCP requires that the model(s) be capable of including plant, animal, hydrological, climatic, and management variables, and simulating interactions among all of these components, the only targets of modeling to date are the fountain darter and SAV, as discussed below. These models are significantly more complex than the Habitat Suitability Analyses discussed in the preceding section because they consider many more of the factors and processes that control species abundance and they are capable of predicting species numbers under varying environmental scenarios, which is a goal of the HCP.

Submersed Aquatic Vegetation

There are six major types of SAV in the Comal system and seven in the San Marcos system, with four common to both rivers. The types and amount of SAV present in both systems change with season and annually. The modeling will need to take into account the variation among the SAV types in their growth dynamics and reproductive strategies, as well as their suitability for providing habitat for the endangered species such as the fountain darter. The goals of the SAV modeling appear to be two-fold: (1) provide habitat as input to the fountain darter

ecological model, and possibly (2) predict SAV (and Texas wild rice) responses to changing environmental conditions.

The SAV modeling team is in the early phases of developing a spatially explicit biomass model of SAV. Because the modeling is still being planned, the following comments are based on the current plans and discussions with the model developers. It is not currently possible to provide comments related to the details of the model's structure or performance, which are likely to change as the modeling proceeds. The discussion below is based on a presentation made to the Committee at its second meeting and subsequent email exchanges and phone conversations with the modelers.

The present focus on SAV modeling is to provide dynamically varying habitat for the fountain darter individual-based model. The proposed SAV model is a somewhat simplified version of longstanding SAV models that have been developed for a single, well-mixed spatial box. The developers want to place the same type of model into a 2-dimensional spatial grid that matches the grid of the fountain darter model. By going from a point (single spatial box) to a spatially-explicit version, representation of the processes of dispersal and recolonization becomes especially important. The modeling will focus first on the Old Channel reach of the Comal system. The grid will either be the same 2-dimensional grid that was used in the habitat suitability analyses (see Box 3-1) and is being used in the fountain darter model, or it will be an aggregated version of that grid (e.g., 0.25 m^2 averaged for 1-m^2 resolution). The spatial resolution needs to be appropriate for modeling SAV, while at the same time, also be appropriate for providing temporally and spatially varying habitat for the fountain darter model.

The model will simulate the processes of photosynthesis, respiration, mortality, dispersal, and recolonization. Photosynthesis, respiration, and mortality rates are likely to be computed daily and used to determine the change in biomass of the SAV in a cell due to intra-cell processes. Dispersal and recolonization are planned to be computed monthly and determine the exchange of biomass from the cell of interest to its neighboring cells (dispersal) and from neighboring cells into the cell of interest (re-colonization). Multi-year simulations will be performed, and the model will generate the biomass (also converted to height and percent cover) for each cell for each day.

Photosynthesis, respiration, and mortality will likely use formulations adapted from existing SAV models. Some of the key existing models are CHARISMA (van Nes et al., 2003), which is 2-dimensional version of the MEGAPLANT model proposed by Scheffer et al. (1993), a series of USACE models (Best and Boyd, 2007a,b), and similarly formulated species-specific SAV models described by others (Cerco and Moore, 2001; Madden and Kemp, 1996; Best et al., 2001).

There is some confusion about terminology used in the SAV modeling effort. The developers understandably referred to their model as agent-based, because that is what Wang et al. (2011) called their Chinese tallow tree model, which the developers cite as the source for their SAV recolonization formulation. Van Nes et al. (2003) also called their model individual-based, which is the same as agent-based, whereby plants are represented as individual units. In using the term "agent-based," Wang et al. (2011) was referring to the spatial aspect of their model (cells as agents), which is a non-standard use of the term. The proposed model would be best described as a biomass-based Eulerian model. While this does not affect the modeling itself, the

fountain darter is truly individual-based and so use of clear terminology will help in communication.

Available inputs for the Comal SAV model include daily values of incident light (grid-wide), substrate type of each cell, and daily water temperature, depth, and velocity in each cell of the grid. Incident light is adjusted for its transmission through the water to the plant surface (i.e., via an extinction coefficient). Typically, light and temperature affect photosynthesis, temperature affects respiration, and mortality is often treated simply as a constant, but could also be dependent on substrate or other environmental variables.

The processes underlying dispersal and recolonization include fragmentation, seed release and subsequent development, and lateral growth. SAV employ a variety of mechanisms for dispersal and recolonization, including seeds, tubers, and fragments (Murray et al., 2009; Ailstock and Shaefer, 2004; Rybicki et al., 2001; Kautsky, 1998), which are affected by velocity, trapping, and viability of floral structure. One idea being considered is the use of a threshold biomass that, once exceeded, would trigger the dispersal and re-colonization. Several options are then available for determining how much of the cell's biomass goes to other cells and the amount of biomass that enters one cell from other cells. One option is simply to distribute the biomass randomly among cells; another option is to weight the destination cells by their quality (e.g., light, substrate, SAV biomass). One can use any number of functions to determine how much biomass leaves and where it goes to. The SAV modeling team indicated that it is exploring the use of the kernel function approach by Wang et al. (2011), as well as other functions.

A critical issue to address is the density-dependence of SAV growth and possibly also of mortality. At some point, SAV biomass cannot increase any further in a cell, as crowding will decrease growth or increase mortality. One approach being considered is to allow the formulations of photosynthesis and mortality to account for the effects of crowding. For example, light attenuation can be dependent on plant biomass so that eventually the plant biomass increases until light is too low for positive growth. Another approach being considered is based on the carrying capacity of each cell, in which the biomass relative to the carrying capacity would be used each day to adjust growth or change in biomass (e.g., like a logistic growth function). As biomass approaches the carrying capacity, the multiplier would act to reduce growth. Representing density-dependence realistically is important because it affects how SAV responds to changes in environmental conditions.

A second critical issue is the treatment of flow and water quality effects on SAV dynamics. Typically, one would specify how one or more of the processes in the SAV model depends on flow directly and indirectly through changes in depth. For example, depth and turbidity would affect light availability. Presently, nutrient limitation is not included in the model formulation, but should be added if it is determined to be an important water quality factor affecting photosynthesis. (Indeed, some of the predecessor models include nutrient limitation.)

A third critical issue is deciding which taxa should be represented in the SAV modeling. One could develop a general SAV model, a model for certain SAV species (such as those preferred by fountain darter like *Ludwigia* and bryophytes), or an SAV model for groups of species that have similar physical structure (i.e., functional groupings). There are advantages and disadvantages to each of these approaches. A general model enables use of information from multiple species but also approximates how any single species will respond. A model for each species requires the most information in order to specify parameter values and other

modeling aspects, but is the easiest to interpret. A set of models based on structural similarity may be the best approach for generating habitat input to the fountain darter model, but may not be a good way to form functional groups to predict SAV responses to environmental variation. That is, the species lumped together may be structurally similar but respond very differently to other factors. Note that the model does not currently include filamentous algae, though it is a preferred habitat type for fountain darter.

Although there are system-wide vegetation maps, calibration and validation of the SAV model will be a challenge. An Applied Research project is currently being conducted to generate a conversion factor from percent cover of SAV recorded in the vegetation maps to biomass being predicted by the model. Accurate conversion is critical because model predictions of biomass will be compared to the spatial vegetation maps of coverage. If the modeling team takes the route of using a generic species or a functional grouping of species, it will not be straightforward to compare model predictions to species-specific field data. Also, the fine spatial scale thought to be needed for compatibility with the fountain darter model may not be ideal for simulating SAV biomass dynamics over seasons and among years. The small grid cells may not allow for accurate averaging of local conditions on a daily or monthly time step to enable the model to simulate six-month changes in vegetation over multiple years.

While it is not yet possible for the Committee to rigorously evaluate the SAV modeling because of it early phase of development, the general approach is reasonable. Clear statement of the goals of the modeling (SAV dynamics or habitat for fountain darter) is critical. Too many compromises to achieve both goals with one model can result in a model that accomplishes neither goal adequately. We suggest a phased strategy of first testing each of the components under known and predictable environmental conditions (e.g., growth under fixed light and temperature), then further testing each component under realistically varying conditions, and then finally calibrating and validating when combined with all of the other processes. Careful attention to formulating a calibration and validation approach that ensures confidence in model predictions for how they will be used in the fountain darter model, and that encompasses the range of conditions to be simulated in the fountain darter model, is needed.

Texas Wild Rice Model

There are no current plans to develop an ecological model for Texas wild rice, which would likely follow on the heels of the SAV ecological model. Rather, efforts are being made in areas of Texas wild rice restoration, such as re-vegetation, transplanting, and increasing the available habitat by controlling invasive species. Additionally, public awareness efforts are focusing on the detrimental aspects of trampling and other habitat destruction. These efforts have proven successful and have increased the total areal coverage of Texas wild rice in the San Marcos River (SWCA, 2014). The habitat suitability analyses can help to guide these efforts by, for example, suggesting what areas are most suitable for replanting. It is recommended that continued efforts focus on Texas wild rice restoration, mitigation, public awareness and improving the existing habitat suitability analyses.

Fountain Darter

The fountain darter modeling effort that is replacing the habitat suitability analyses is truly a population modeling approach. The population modeling approach will address the shortcoming of habitat-based analyses, which can only predict changes in habitat capacity and not fountain darter abundance. However, there is also the possibility that a true population model will not generate predictions with sufficient confidence for it to stand alone as the only quantitative tool to assess flow and habitat effects on fountain darter population dynamics.

The currently envisioned model would simulate individual darters initially in a small area of the Comal River (e.g., 400-500 meters of the Old Channel) on a 2-D grid. The grid would be thousands of horizontal cells, each with an area about 0.25 m^2. Velocity and water depths would be obtained from the hydrodynamics modeling and inputted for each cell by converting the predictions from the hydrodynamic modeling grid to grid layout in the fountain darter model. Presently, hourly velocities and water depths for each cell in the individual-based model (IBM) would be obtained for steady-state hydraulic simulations of 1 cfs increments for 30 to about 80 cfs. The user would select a cfs value for the entire simulation or they could string together different fixed flows into a single time series (e.g., 10 days at 31 cfs and then 10 days at 40 cfs). Each cell in the IBM would also get assigned a vegetation type that would be updated three to four times per year (i.e., abrupt changes). Hourly water temperature, assumed uniform over the spatial grid, would also be inputted.

Individual growth, mortality, and reproduction would be evaluated daily, and the local population would be simulated for ten or so years. Growth would be determined by the average duration an individual stays in a stage (i.e., age determines development). The underlying assumption is that while individuals may be food-limited (i.e., do not grow at their maximum possible rate), all individuals, regardless of their habitat and timing, grow at the same rate and that rate is what has been observed in the empirical data on stage durations. Mortality rate would depend on stage, and reproduction would generate eggs for the next generation. Movement would be evaluated hourly and individuals would stay in vegetated cells. If the cells became denuded of vegetation, then the fish move to vegetated cells within some neighborhood. There is presently a negative feedback (density-dependence) on recruitment to enable a stable population to be simulated. This is calculated for the entire model grid and the result is that the mortality rate increases as the number of vegetated cells in the system decreases. There are plans to use the new SAV ecological model for vegetation changes over time as input to the IBM. The model is in the planning stages and so some variables, like velocity and vegetation type, are inputted as place-holders for use later to relate to growth, mortality, reproduction, or movement.

The proposed approach uses a spatially explicit, individual-based methodology to simulate the growth, mortality, reproduction, and movement of individuals; the sum over individuals is then the population-level outputs. Individual-based modeling is seeing a rapid rise in use for fish and other taxa (DeAngelis and Mooji, 2005). Following individuals has several advantages over the more traditional state variable or age/stage structured approaches. The shift from Eulerian (change in mass at a location) to Lagrangian (tracking individuals) models enables explicit treatment of local environmental effects, easier simulation of movement, inclusion of all possible effects of variation in size and other traits, and tracking of individuals' experiences as they move through time and space. The same factors and processes are considered in the more aggregated models but often are implicit. These features are highly desirable in a model of

fountain darter to enable realistic simulation of how spatial and temporal variation in habitat affects their population dynamics.

An individual-based approach also has some critical challenges, especially when embedded into management decision-making situations. The idea of following individuals through time and space is intuitively appealing but the confidence in model predictions relies on the availability of data and information to enable calibration and validation of both individual-level variables (e.g., movement tracks) and population-level variables (e.g., abundance, spatial distributions, density-dependence). The extensive data and information needed for model calibration and validation are rarely available for a species in a specific location. Thus, such analyses are better suited for predicting relative changes in population abundance and distribution under representative conditions, rather than absolute abundances for specific times (years) and locations. This should be kept in mind when making management decisions that require absolute numbers of individuals expected in the system in a given year.

Spatial modeling of population dynamics is increasing because the questions often involve spatial aspects that are difficult to treat implicitly in spatially aggregated models. The HCP is an excellent example where the questions being asked can be addressed more easily with explicit representation of space within the population model. While it is intuitive that spatial problems would benefit from a spatially explicit modeling approach, the use of a spatial grid also involves some additional effort. A spatially explicit model requires the data to be spatial in order to ensure that not only is the total population being simulated realistically, but also that the growth, mortality, and reproduction within different local regions, and movement among spatial areas, are also realistic. Modeling behavioral movement is receiving increasing attention (Watkins and Rose, 2013), but there is presently no generally accepted algorithm for simulating fish responses to changing environmental and habitat conditions.

Two additional aspects of the modeling are the decision to simulate the population over multiple generations and to simulate the fountain darter population rather than the food web. It is important to be able to simulate multiple years of darter population dynamics in a self-regenerating manner (adults give rise to the young who grow up to be adults). A major question to be addressed with this model that cannot be addressed with habitat suitability analysis is the decline and recovery of fish over multiple years given patterns of drought, flood, and other hydrological conditions. This is most effectively simulated with a population model that is self-regenerating. Focus on the population rather than on the food web is a pragmatic decision because, while food web interactions are very important, it can be difficult to quantify the many possible interspecific interactions typical of food webs.

In developing the fountain darter model, modelers should pay particular attention to the following topics:

- How movement is represented
- Clear documentation and justification for how flow, temperature, and vegetation are included in the growth, mortality, reproduction, and movement relationships
- How density-dependence is included
- Using the model to generate predictions of the population responses to various combinations of years with scour events and droughts

- Bookkeeping in spatially explicit IBMs (either true individuals or super-individuals) can be tricky and the numerical precision of model simulations needs to be demonstrated
- Calibration and validation, which are needed to ensure sufficient model credibility
- Careful tracking of uncertainty
- Expectations are high because much discussion has pushed things to the ecological modeling and the term "predictive" has been used. Clarification of what the darter modeling can do and cannot do would be wise.

The model is being developed in Netlogo, with an option to move to a more primitive but faster language like C++. The development of the population model would also be an opportunity to revisit the influence diagrams found in the HCP and, as discussed later, develop more rigorous formal conceptual models for how factors affect darter population dynamics and how management actions directly and indirectly affect their vital rates.

The proposed modeling approach is a scientifically sound way to address the limitations of habitat suitability analyses, and a spatially explicit IBM has many attractive features, along with challenges in terms of model formulation, calibration, and validation. The modeling is in its initial stages with many details not yet available. The details in this type of modeling are very important because there is no standard method for specifying the processes and spatial and temporal scales in the model. One challenge is that population modeling is a scientific process that involves the judgment of the modeler. While this is true of all modeling, it is particularly apparent with population modeling like that being used for the fountain darter. For example, statistical modeling uses data to determine which model is best, and all hydrodynamics models solve the same basic set of fundamental physics equations (i.e., conservation of mass and continuity of momentum). Developer decisions focus more on details, such how to transform the data and outliers for statistical analysis, and how to set up the model grid and how to deal with subgrid scale processes (e.g., turbulence) for hydrodynamics. Fish population modeling does not have sufficient data to use the statistical modeling approach of data determining the best model. Also, population modeling cannot rely on fundamental equations like hydrodynamics modeling can. Thus, decisions about model structure and what to include and exclude in fish models get pushed more towards the judgment of the modeler (i.e., "the art of modeling"). The strong role of the modeler's judgment in population modeling does not weaken its power and utility, but it does make model selection and implementation more difficult to document and justify.

The fountain darter modeling would benefit from proceeding in a stepwise, transparent, and modular manner with intermediate products that could eventually be used to build the full-fledged individual based model. This includes the reporting of analyses that support each of the major submodels of growth, mortality, reproduction, and movement. Such analyses should discuss how the effects of flow, temperature, and structural habitat on each of these major processes will be represented in the model. Such a stepwise approach would also allow for model evaluation and reflection. Second, it would also be worthwhile to evaluate whether the fine-scale spatial resolution currently being considered (0.25 m^2) for the model is really needed. Third, careful design of a strategy for calibration and validation is needed that includes both classical predicted-versus-observed comparisons (Stow et al., 2009), pattern-oriented evaluations (Grimm et al., 2005), and uncertainty analysis. The developers may also want to consider isolating the population dynamics in a simplified model version without explicit space, and expanding the population model to include the dynamics of plankton, SAV, and darter (i.e.,

create a very simplified food web or multi-species model). Many of these suggested steps in the development of the fountain darter model could be viewed as their own products that would expand the modeling toolbox for fountain darter.

Comal Springs Riffle Beetle

In 2013, the HCP Ecosystem Modeling Team completed a literature review of the CSRB and other riffle beetle species (EA HCP Ecosystem Modeling Team, 2013) with the intention of determining what is known about these species and how it could be used for exploring new modeling approaches for the CSRB and its habitat. This document also provides a short review of several modeling approaches that have been used more generally for aquatic macroinvertebrates. The limitation is not in the availability of modeling approaches but rather that relatively little is known about the basic biology and natural history of the CSRB. Indeed, much of the literature review was for related beetle species that are found in the Comal Springs region; how well these species may represent the CSRB is unknown.

The report authors eliminated from consideration those modeling approaches that require intense data incorporation because they perform poorly outside of the range of conditions represented by such data. Two generalized modeling approaches, the Bayesian Belief Network analysis and Fuzzy Logic modeling, were identified as possibilities because they can be used when there is large uncertainty in the input data and they can also incorporate best professional judgment. Given the current understanding of the basic biology and ecology of CSRB, the Committee agrees that these modeling approaches are appropriate starting points for providing more robust and quantitative projections of CSRB habitat that could serve to inform long-term population-based modeling efforts. The Committee recommends that the Applied Research Program explicitly seek to provide essential data required by the models and that the HCP include an aquatic entomologist or freshwater invertebrate ecologist to help guide this research.

The HCP acknowledges that habitat requirements for the CSRB, particularly regarding subsurface habitats, are unknown. Also, the HCP states that more extensive work is required to evaluate and assess water quality tolerances of the CSRB. At the present time, the primary measure of habitat quality for the beetle found in the HCP is qualitatively (and possibly only anecdotally) linked to silt deposition. Additional field studies are warranted to assess more quantitatively the negative effects of increased siltation and how these effects interact with changing flow conditions. Further, critical life history information and better surveys for additional CSRB habitat are needed. Answering the following questions would provide information needed for using the proposed modeling approaches from the 2013 literature review.

- What is the basis for the assumption that silt deposition represents an important environmental effector of CSRB population densities?
- How does siltation quantitatively affect the known habitats of CSRB, and are there habitats that may act as refugia during times of heavy deposition?
- Are there quantitative relationships between silt-free gravel and cobble area with beetle population densities?
- How many generations occur throughout the year for the CSRB and how does variable flow and sedimentation affect food availability and the beetle's population biology?

- Are there invasive predators or competitors in these systems that might apply biotic control on the population numbers?
- What other factors are likely to affect the population biology and ecology of CSRB?
- How reliable is the cotton lure sampling method for quantitatively estimating densities of both adult and immature life stages of the CSRB?

The population measurement goal for CSRB is to maintain greater than or equal to the median densities observed over the past six years of EAA Variable Flow Study. Some of the research ideas above might become the focus of projects under the Applied Research Program, as discussed in Chapter 5.

A CONCEPTUAL MODEL OF THE COMAL AND SAN MARCOS ECOSYSTEMS

This chapter has discussed the current status of and future efforts to model the indicator species in the Edwards Aquifer system, including fountain darter, Texas wild rice, and Comal Springs riffle beetle. Regardless of whether the habitat suitability analyses or the ecological models are chosen going forward, there would be substantial benefit to gaining a more holistic understanding of the spring and cave species as members of communities of organisms interacting with each other and with the environment. There is evidence that the EAA would like to move in this direction. For example, already the HCP monitors fountain darters both by darter abundances and darter habitat. Clearly, the habitat measure is an indirect composite assessment that includes factors such as availability of food, mating partners, nursery grounds, predator refuge, etc. However, there appears to be little knowledge of bottlenecks and other limiting factors that ultimately affect darter survivorship during low spring flow rates. That more darters are found in bryophyte beds could reflect food availability or predator avoidance, but other habitats could be more important with respect to mating, egg attachment and recruitment, and survivorship during low flow rates. The snap-shot pictures of darter location that show high densities in bryophyte patches and lower densities elsewhere might be artifacts of a dynamic pattern in which darters migrate between habitats differing in quality and availability of prey, mates, spawning, and other habitats. While much important information is known about fountain darters, particularly compared to the other endangered and threatened species, and the EAA and their scientists might be able to answer the above questions knowledgably, it is unclear how that knowledge will ultimately contribute to maintenance and recovery of the endangered species because there is no apparent structural mechanism for prioritizing data needs and knowledge gaps. Similar issues and concerns could be raised for all species, target and non-target.

One approach to prioritizing and focusing EAA's monitoring and research efforts would be for EAA to develop a series of conceptual models, perhaps with increasing resolution, to highlight the important and potential drivers of population regulation in the covered and indicator species. The current species-centric approach (i.e., individual conceptual models for each species) is important for the population-level analyses, but does not allow for an easily articulated and communicated ecosystem view, both within each system and across the two systems. The EAA should strive for producing a general model in which all covered species, their important driving factors (both abiotic and biotic), and all available management actions are linked within a common framework. It is timely to assess the state-of-knowledge about the

Comal and San Marcos ecosystems, given the new data and information becoming available as a consequence of the HCP and the Applied Research Program. The development of a series of conceptual models would also be an opportunity to get feedback from, and create common understanding among, stakeholders, scientists, and the general public and hence broaden the scientific pool of experts knowledgeable about the systems. This is especially important if the presently held views of how the systems will respond to changes in flow turn out to be incorrect.

Examples of systems where conceptual models have been developed include such large-scale systems as (1) the Sacramento Bay Delta, where conceptual models for fish habitat, riparian vegetation, and other elements of the natural system help guide restoration activities (DiGennaro et al., 2012; NRC, 2012; Baxter et al., 2015; http://www.science.calwater.ca.gov/drerip/drerip_index.html), (2) the Chesapeake Bay, where oxygen and harmful algal bloom dynamics are a major concern (http://ian.umces.edu/ecocheck/); and (3) the St. Johns River in northeastern Florida where water diversions from the river are being evaluated for their impact on macroinvertebrates, SAV, fish and other wildlife (NRC, 2012). More generalized conceptual models have been used in the study of alternate stable states in shallow lakes (Scheffer et al., 1993; Drenner and Hambright, 2002), trophic dynamics within ecosystems (Carpenter et al., 1985; Oksanen, 1991), the organization and structure of communities along a riverine gradient (Vannote et al., 1980), and metabolic and physiological scaling within ecosystems (Brown et al., 2004).

It should be a top priority for the EAA to develop a conceptual model, or a series of models of increasing resolution, that show how water quality and quantity, other biota, and restoration and mitigation activities are expected to interact with the indicator species, as well as with all covered species. Within the conceptual model, boxes could be used to represent targets of the monitoring program, while arrows linking the boxes could represent quantitative or empirically derived relationships between the boxes based on research. Such interactions for which too little data are available to establish empirical relationships could be targeted for modeling and further research during the permit period. Conceptual models could be based loosely on the influence diagrams in Hardy (2009). In addition to considering each species individually and being based on different forcing factors, composite ecosystem-level diagrams for each spring that include known and hypothesized interactions of both biotic and abiotic driving and response factors could help provide a means of focusing and prioritizing EAA funding, monitoring, and research. For example, not only would it be informative to combine Figures 4 to 7 (Hardy, 2009), it would be very informative to see how flow quantity and quality were linked to all three indicator species (and the food web in general) within the same conceptual model. In other words, where are there expected to be common, complementary, synergistic, and contradictory effects of environmental forcing factors across the species of concern and how might species interactions vary with these forcing factors?

The overall HCP is based on the assumption that a minimum spring flow (of acceptable quality) will be good for all species concerned. In other words, if there is spring habitat, spring species will survive, which is a logical assumption. The conceptual model could provide an overall view of how flow relates to population sizes. On the other hand, minimization and mitigation measures may not carry equal or similar benefits to all species, or at least this seems less likely. Manipulations of habitat (restoration of native vegetation, reduction of siltation) and nutrients (isolation of the golf course and other forms of runoff) could affect food availabilities

for grazers, which could in turn affect grazer populations, and these effects could reverberate up through the food web.

The use of three indicator species to protect all species is based on the assumption that all habitat minimization and mitigation measures of the HCP for these three species would be sufficient to protect all covered species, as well as all species that have not been included as covered species in the HCP. The conceptual model should demonstrate the basis for this assumption, highlighting where knowledge exists to support the assumption, but also where information may be needed.

The external review (EARIP, 2012, Appendix I) of Hardy (2009) points out that ultimately ecosystem function may depend on factors (e.g., non-native fishes) not included in the habitat suitability analysis, especially over a longer term, as several years to decades may be required for their roles to become evident. They stated that “for the target organisms and the habitats within which they live to achieve recovery and persist over the long term, additional information is needed to understand, anticipate, and manage these factors as much as possible.” An added benefit of the conceptual models would be to highlight these other important factors, determine whether and how they can be incorporated into the ongoing ecological models for SAV and fountain darter, and allow the EAA to prioritize the research and monitoring required to support model development.

The assembled suite of conceptual models, from population dynamics of key species to ecosystem dynamics of each spring, would provide a foundation for the ongoing data collection and modeling activities and also for communicating data analyses, modeling output, and decisions to collaborators and stakeholders. The development of effective conceptual models is not trivial and should include broad participation from researchers and stakeholders to ensure support. It would also be advisable for the EAA to devise a mechanism for periodical review and refinement of all conceptual models and their various components as monitoring and research provide new insights.

CONCLUSIONS AND RECOMMENDATIONS

The approach to ecological modeling taken in the HCP of combining field data, habitat suitability analysis, and modeling of population dynamics is appropriate and can support the management decisions that will need to be made as the HCP proceeds. There are, however, several aspects of the analyses to date that should be adjusted to ensure that robust conclusions are obtained. Recommendations about the field data are found in Chapter 4 and the Committee’s evaluation of the Applied Research projects is the subject of Chapter 5. The conclusions and recommendations below focus on the habitat suitability analyses and the planned ecological modeling.

The goal of the SAV modeling, which is in its early stages, should be clarified. Whether the goal is to simulate SAV biomass dynamics or to simulate habitat for the fountain darter model will affect how many models are needed and how each model is formulated and tested. Similarly, key issues about spatial resolution and whether to model specific species or a generic SAV species depend on the goals of the modeling. Once the goal is determined, a strategy for model design, calibration, and validation should be developed.

Given the absence of a planned ecological model for Texas wild rice, the current habitat suitability analysis should be treated as an hypothesis and tested for robustness throughout the San Marcos River. The EAA should consider designing minimization and mitigation measures for Texas wild rice in a manner to provide experimental analysis of the habitat suitability results. For example, the minimization and mitigation activities could be used to test the validity of using water depth and velocity as the only predictive variables for optimal habitat for Texas wild rice. Similarly, one could use replicated reference and control areas to provide explicit tests of the efficacy of replanting and to quantify the roles of discharge, competition, and other factors that may limit Texas wild rice growth and survival.

The ongoing effort to build an individual-based model for fountain darter is a scientifically sound approach for modeling population dynamics that will require extensive data for model formulation, calibration, and validation. Ensuring that the model results are properly interpreted (i.e., viewed with appropriate confidence) will be critical to the success of these efforts. Fortunately, the model is being developed with a healthy mix of modelers and field ecologists who know the system, there are well-defined questions that are answerable by the modeling, and there is an opportunity to influence data collection to get specific information needed for the modeling. Some of the interactions between key players that should be expanded and strengthened include (1) hosting workshops at key times (to define the questions, formulate the model, and present preliminary results), (2) making clearer links between the monitoring data and the Applied Research projects and how both will be used to inform the modeling, and (3) engaging modelers with experience in developing similar individual-based models.

The habitat suitability analyses done for fountain darter could act as a "back-up" to the individual-based modeling and provide additional quasi-independent results to support a weight of evidence approach for fountain darter. Habitat suitability analyses are tied closely to data, they are easy to explain, and the reporting of the amount of high quality habitat has intuitive appeal. Although the habitat suitability approach does not convey fish abundance like the population modeling, the latter requires more data, greater mechanistic understanding, and is more challenging to explain. Thus, pursuing both approaches has merit, as has been borne out in the Everglades restoration efforts, which started with habitat suitability analyses, went to population and community modeling, and then either maintained or re-started the habitat suitability analyses. The habitat-based analysis for fountain darter reported in the HCP (not the two Hardy analyses) should not be used without significant revision.

If the CSRB is to be an adequate indicator of some of the other ESA-listed species, it is critical to have a much deeper understanding of the spatial distribution, range of potential habitats, and natural history of the CSRB. This natural history includes understanding the number of generations per year, cohort synchrony or asynchrony, the times of year for reproduction, and the biotic and abiotic variables that influence these dynamics. Furthermore, a better understanding of the optimal CSRB habitat is needed to understand how changing flow conditions will impact CSRB.

Although the HCP has identified the CSRB as a primary species for monitoring and calls the beetle an indicator of other species that are not being monitored, the degree to which CSRB is a reliable indicator is presently not well understood nor has it been objectively tested. Details

about how to explore the relationships between CSRB and other species are provided in Chapter 4.

It is recommended that as a top priority the EAA develop an ecosystem-based conceptual model, or a series of models of increasing resolution, that show how water quality and quantity, other biota, and restoration and mitigation activities are expected to interact with the indicator species, as well as with all covered species. Boxes in the conceptual model would represent targets of the monitoring program, while arrows linking the boxes would represent quantitative or empirically derived relationships between the boxes based on research. Such interactions for which too little data are available to establish empirical relationships could be targeted for monitoring and further research during the permit period.

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4

Monitoring

The Habitat Conservation Plan (HCP) requires the development and implementation of a monitoring plan throughout the 15-year term of the Incidental Take Permit to "…provide information for the U.S. Fish and Wildlife Service (FWS) and the Applicants to: (1) evaluate compliance with the HCP; (2) determine if progress is being made toward meeting the long-term biological goals and objectives; and (3) provide scientific data and feedback information for the Adaptive Management Process" (EARIP, 2012, page 6-2). To meet these goals, the monitoring plan must provide comprehensive information about key aspects of the hydrology and ecology of the aquifer and spring systems including groundwater flow and quality, surface water flow and quality, and selected biological habitats, populations, and communities. It must provide data that can be used to detect changes in spring flow and how the ecological system of springs and rivers responds to changes in flow. It must also allow detection of how the ecological system responds to other forcings such as incremental climate change, land-use and land-cover changes in the stream watersheds, mitigation and minimization efforts, and introductions or elimination of non-native species. Finally, the monitoring plan needs to provide basic information to support the development and evaluation of hydrologic and ecological models designed to understand and forecast spring flow and target species responses to changes in spring flow.

In this first report the Committee focuses on the biomonitoring and water quality monitoring programs. Collectively, these two somewhat independent programs are intended to provide the observational data needed to assess whether the HCP is meeting its goals of protecting the target species as well as collecting the ancillary biological community and water quality data required to identify plausible mechanisms for observed changes in the target species abundance or distribution. In this chapter we describe these two monitoring programs, critically evaluate whether the programs are likely to achieve these goals, and offer a series of recommendations to improve monitoring as the program proceeds. Performance monitoring of ongoing or proposed mitigation and minimization measures is beyond the scope of this initial report.

BIOMONITORING PROGRAM

The EAA has developed a complex biomonitoring plan that covers many physical, chemical, and biological aspects of the San Marcos and Comal spring and river systems. While the program is focused on the abundance and spatial distribution of the target species (fountain darter, Texas wild rice, Comal Springs riffle beetle), it also samples the biological communities in which these species are embedded and some aspects of the physical and chemical environment such as water temperature, flow, and basic water quality variables. The biomonitoring program

builds on past observations and uses a complicated combination of whole system mapping, index stations, and a series of longitudinal sampling stations depending on the particular parameter being measured.

Biological studies have been conducted in the Comal and San Marcos Springs areas by various individuals, agencies, and universities since the late 1800s when the fountain darter was first collected in the San Marcos and Comal Rivers (Schenck and Whiteside, 1976). In 2000, monitoring in these spring systems was organized under the Edwards Aquifer Authority Variable Flow Study. This study ended with the formal adoption in 2013 of the HCP, under which biological monitoring continues. Under the HCP comprehensive biological monitoring occurs two to four times per year at selected locations. In addition, high or low flow conditions can trigger additional sampling episodes.

Details of the biomonitoring program are provided in Tables 4-1 and 4-2 (for 2013) and Figures 4-1 through 4-5. To summarize briefly, water temperature is measured continuously at various locations in the spring and river systems. Other basic water quality variables (such as pH, dissolved oxygen, conductivity, and water depth) are measured twice a year at locations where fish sampling occurs. In addition, when triggered by low-flow thresholds, samples for nutrient analyses are taken from multiple locations along both river reaches. Aquatic vegetation is mapped throughout the entire river systems every five years, though in the San Marcos River Texas wild rice is mapped annually. Vegetation in the so-called "representative reaches" is mapped twice per year and when triggered by low-flow conditions. Fountain darter abundance and distribution are measured twice annually in the "representative reaches" and at additional sites. Fish community sampling is done in selected reaches (not the "representative reaches") twice per year and when triggered by low-flow conditions. San Marcos salamander and Comal Springs salamander monitoring is done at three and four locations, respectively, twice per year. Macroinvertebrate community sampling in the "representative reaches" occurs twice per year.

Multiple components of both spring systems are monitored using five locational strategies (Box 4-1). System-wide sampling includes the entire Comal and San Marcos Rivers from the springs to the confluence with the Guadalupe and Blanco Rivers, respectively. Within these rivers, discrete points are sampled continuously for water temperature and occasionally for other water quality parameters during low-flow-triggered sampling events. "Representative reaches" are short segments of the rivers that are used as index stations and, similarly, "representative springs" are index sites at selected springs. Finally, additional sampling is also conducted at non-index reach sites.

It is important to note than none of the sampling locations were selected using randomization procedures. Therefore, it is inappropriate to use observations derived from the sampling locations to make inferences concerning the entire river or spring systems (with the exception of whole system mapping of vegetation). Nevertheless, the "representative reach" locations were selected purposely to cover the full range of environmental conditions and habitats exhibited throughout the entire river, and comprehensive sampling in these reaches can discern relationships among the physical and chemical environment and various biological populations and communities. Thus, these reaches can be useful as index sites to monitor long-term change, and the Committee recommends that sampling in these sites continue. But because the label "representative reach" can falsely imply that the sites can be used to scale to the entire river systems, the Committee suggests that the term "index or indicator site" or even "long-term index or indicator site" be used to more accurately describe these locations. Care should be

taken to clarify that data from these index sites are not necessarily scalable to the entire river system. For the remainder of this report, the term "representative reach" is replaced with "index site" or "index reach."

It is possible that the EAA will determine that from time to time it is important to be able to scale inferences on population density of fountain darters or other target species to the entire spring and reach system. For example, to be in compliance with the incidental take permit, the EAA may decide it needs to estimate incidental take from the entire system, not just that in the study reaches. In that case, one way to make inferences on the entire reach would be to do a special study to test how representative the index reaches are of the entire system, similar to what is being done now with mixed results for the submerged aquatic vegetation. An alternative approach would be to invoke some sort of randomization into the sampling protocols. One possibility would be to use the whole system aquatic plant mapping that is done every five years to stratify all the reaches by vegetation type and randomly sample within these strata for biological population and community variables. If aquatic plants are major drivers of fish and macroinvertebrate population and community distribution and abundance, then the relationships derived between abundance and plant community type could be used to scale up to the entire river system. Potential sampling of fountain darter in a manner that would be scalable to the entire system is discussed further in the section on biomonitoring of fountain darter.

Box 4-1 Spatial Sampling Strategies Used For Biomonitoring Program

1. <u>System-wide sampling</u> for macrophytes
2. <u>Select longitudinal locations</u> for water temperature, water quality, and fixed photography
3. <u>"Representative reach" sampling</u> for macrophytes (SAV) and fountain darter netting
4. <u>Representative springs sampling</u> for salamander and invertebrate sampling
5. <u>River section/segment sampling</u> for fountain darter and community sampling for fish and macroinvertebrates.

Table 4-1 Components and Sampling Dates of the 2013 Biomonitoring Events in the Comal System

What	When	Where*	Method	Recurrence
Water quality	Continuous for temperature	Locations not disclosed	Thermistors	Every 10 minutes
	August 12 for many parameters	12 sites (Fig. 4-1)	Grab samples	During critical low flows
	Every Friday for pH and CO_2	5 sites (Fig. 4-2)	Texas Naturalists	Weekly
Vegetation mapping	Jan-Feb	Everywhere	Kayak and GPS	Every five years
	April, Sep., Oct.	4 Index Reaches (Fig. 4-2)	Kayak and GPS	Twice a year and during critical low flows
Fountain darter sampling	April, July, August, October	4 Index Reaches (Fig. 4-2)	Drop Net	Twice a year and during critical low flows
		7 locations (Fig. 4-1)	Timed Dip Net	Twice a year, but will discontinue if presence/absence continues
		4 Index Reaches (Fig. 4-2)	Presence/absence Dip Nets	Twice a year, but will discontinue if timed dip nets continue
		Landa Lake	SCUBA	Not clear
Fish community sampling	April, August, October	Certain river sections (Fig. 4-1)	Seines and underwater surveys	Twice a year and during critical low flows (new in 2013)
Comal salamander observations	April, August, Sept., October	4 spring locations (Fig. 4-2)	SCUBA/snorkel	Twice a year and during critical low flows
Comal invertebrates	May-June, Nov.	3 spring locations (Fig. 4-2)	Drift net	Twice a year
	May-June, Sep., Oct., Nov.	10 springs at each of 3 locations: Spring Run 3, along the western shoreline of Landa Lake, and near Spring Island	Cotton lures	Twice a year and during critical low flows
Macroinvertebrate community sampling	April, Oct.	4 Index Reaches (Fig. 4-2)	Triple H sample	Twice a year (new in 2013)

SOURCE: BIO-WEST (2014a).
*Index reaches are called "representative reaches" in BIO-WEST (2014a).

Table 4-2 Components and Sampling Dates of the 2013 Biomonitoring Events in the San Marcos System

What	**When**	**Where***	**Method**	**Recurring?**
Water quality	Continuous for temperature	Locations not disclosed	Thermistors	Every 10 minutes
	Not done in 2013	18 sites (Fig. 4-3)	Grab samples	During critical low flows
Vegetation mapping	April-May	Everywhere	GPS	Every five years
	Oct.	3 Index Reaches (Fig. 4-3)	GPS	Twice a year and during critical low flows
Fountain darter sampling	May, July (dip net only), October	3 Index Reaches (Fig. 4-4)	Drop Net	Twice a year and during critical low flows
		4 locations (Fig. 4-4,4-5)	Timed Dip Net	Twice a year (3rd sampling event not explained)
		15-20 sites in 3 Index Reaches (Fig. 4-4)	Presence/absence Dip Nets	Twice a year (3rd sampling event not explained)
Fish community sampling	May, Oct.	4 segments (Fig. 4-4, 4-5)	Seines and visual underwater surveys	Twice a year (new in 2013)
San Marcos Salamander	May, Oct.	3 locations (Fig. 4-3)	Snorkel/SCUBA	Twice a year
Texas Wild Rice	Aug-Sept.	Everywhere	Full system mapping via GPS	Annually
	Feb., Apr., May, Oct., Nov.	2 reaches	Physical observations, lots of measurements	Twice a year, and during critical low flows in vulnerable areas
Macroinvertebrate community sampling	May, Oct.	3 Index Reaches (Fig. 4-3)	Triple H sample	Twice a year (new in 2013)

SOURCE: BIO-WEST (2014b).
*Index reaches are called “representative reaches” in BIO-WEST (2014b).

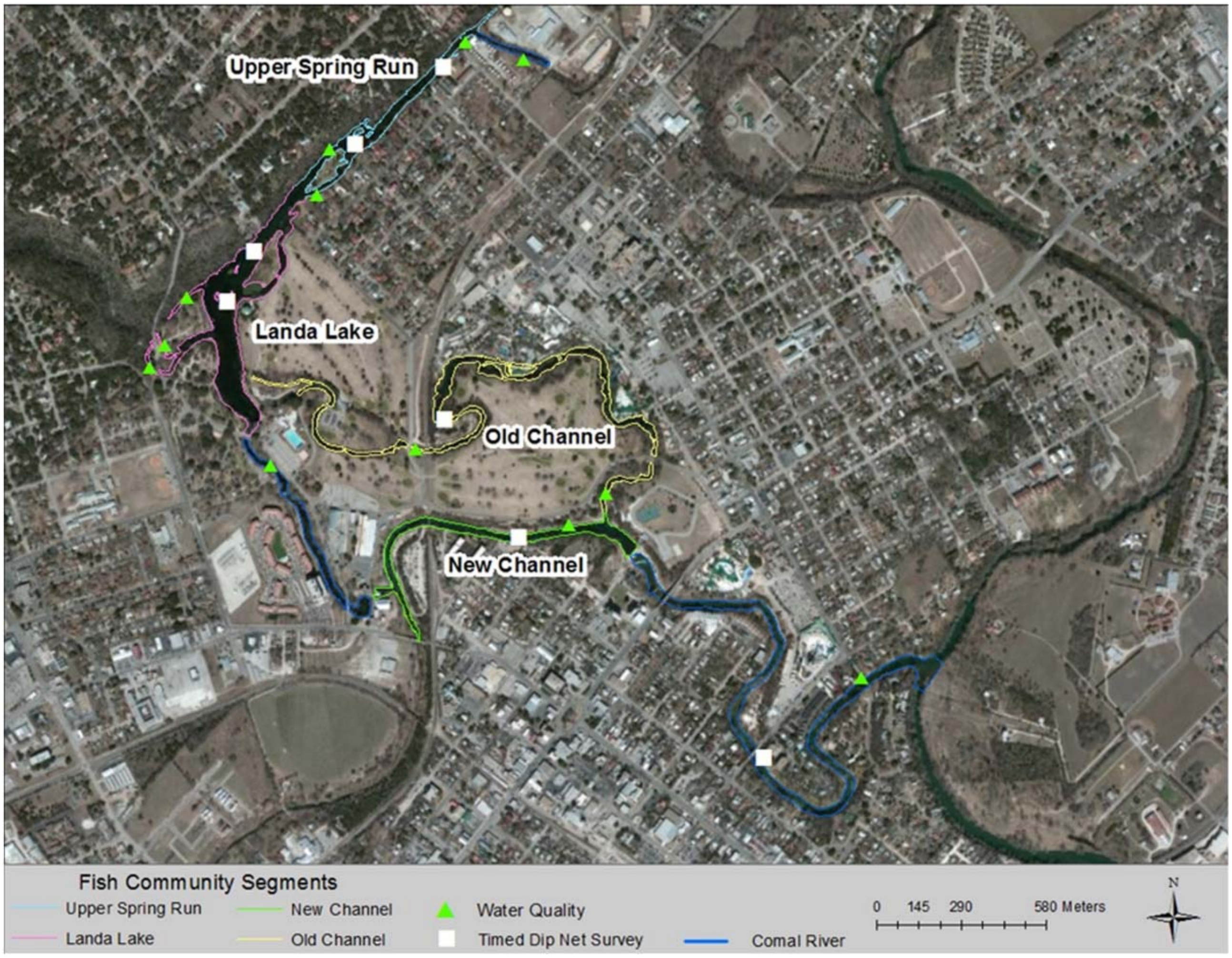

FIGURE 4-1 Fish community, water quality, and fountain darter timed dip net surveys within the Comal River study area.
SOURCE: BIO-WEST (2014a).

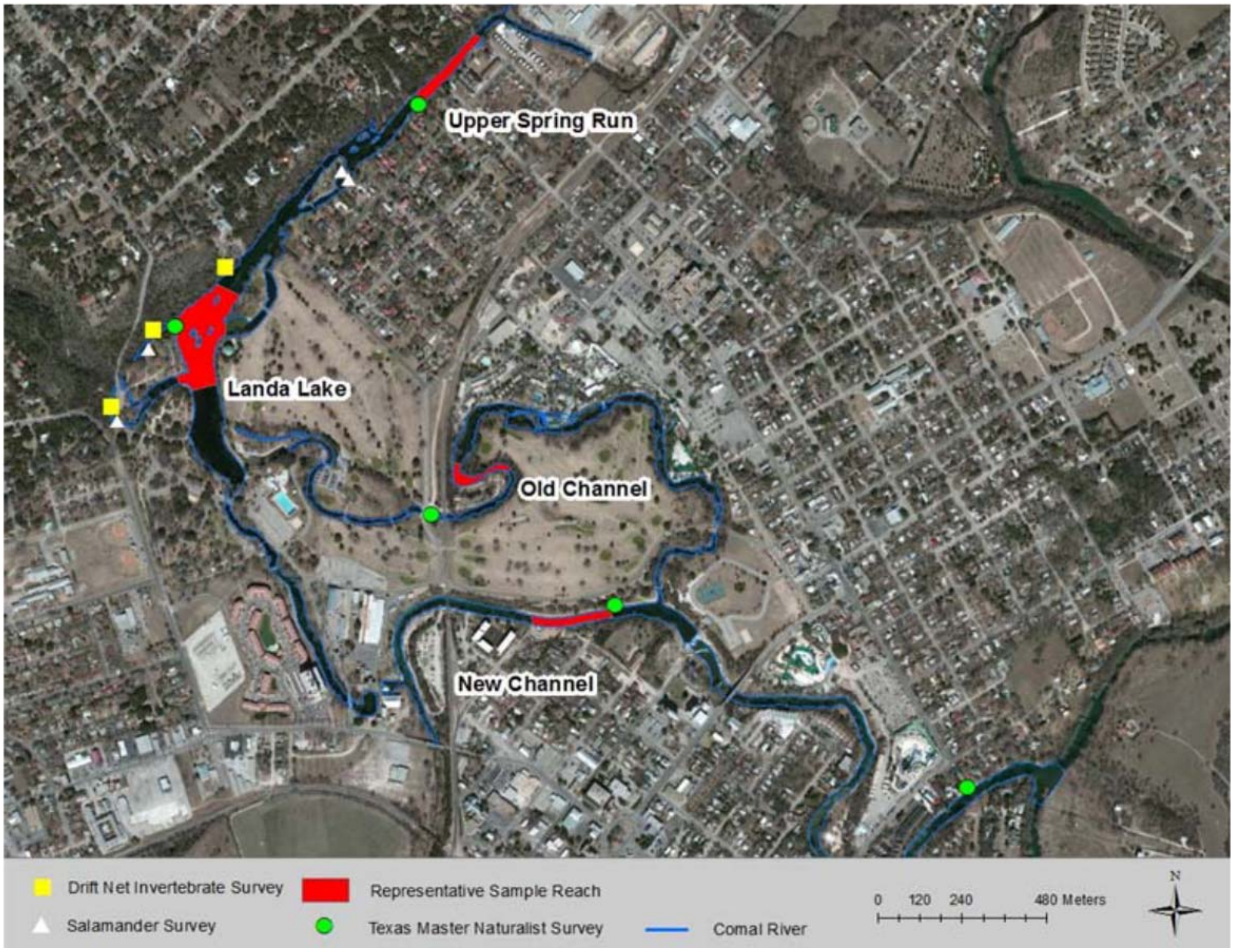

FIGURE 4-2 Invertebrate, salamander, Texas Master Naturalist, and representative sample reaches (includes aquatic vegetation mapping, drop-net sampling, presence/absence dip net sampling, macroinvertebrate community) surveys within the Comal River study area.
SOURCE: BIO-WEST (2014a).

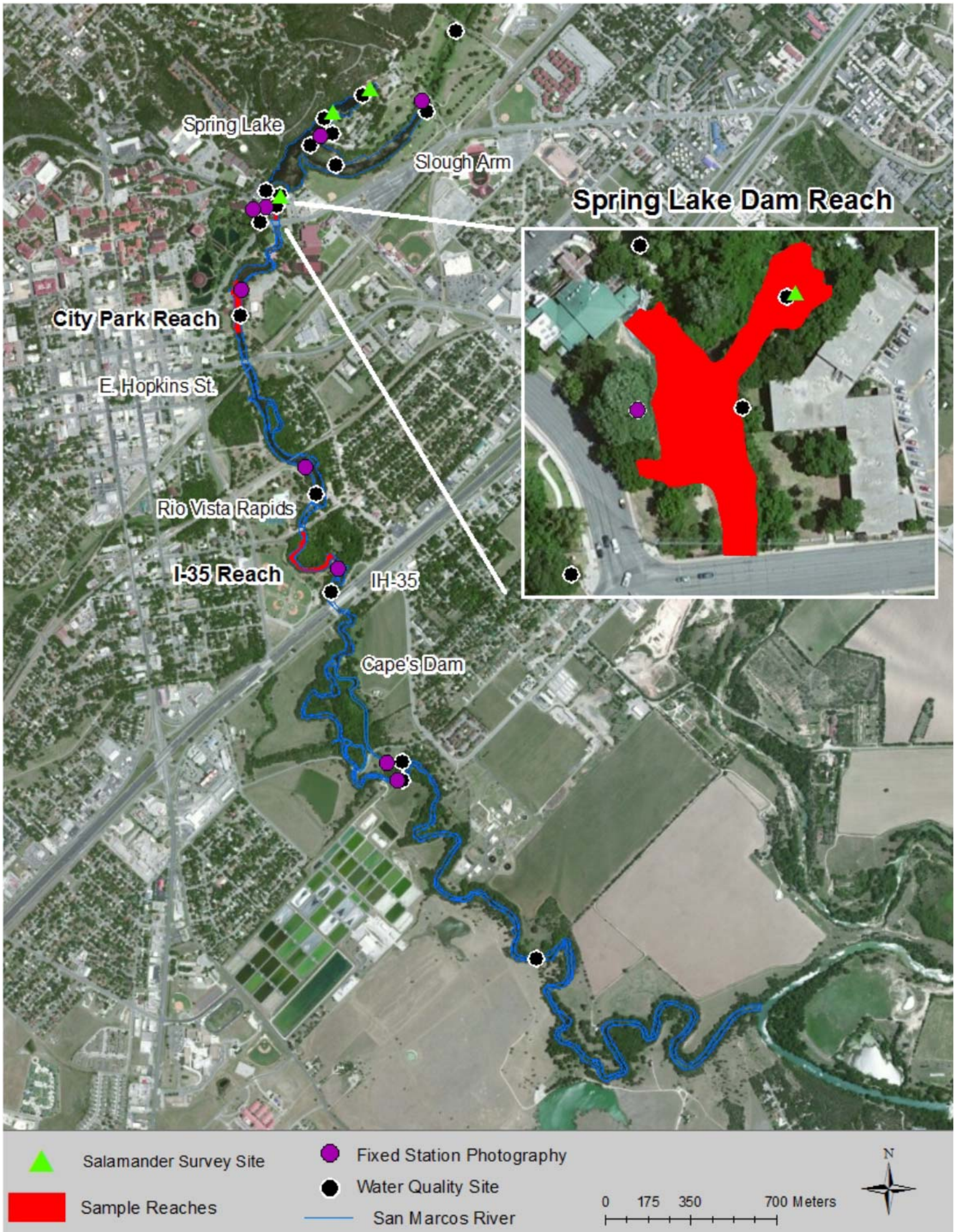

FIGURE 4-3 Upper San Marcos River representative sample reaches, salamander count sites, water quality sampling and fixed station photography sites.
SOURCE: BIO-WEST (2014b).

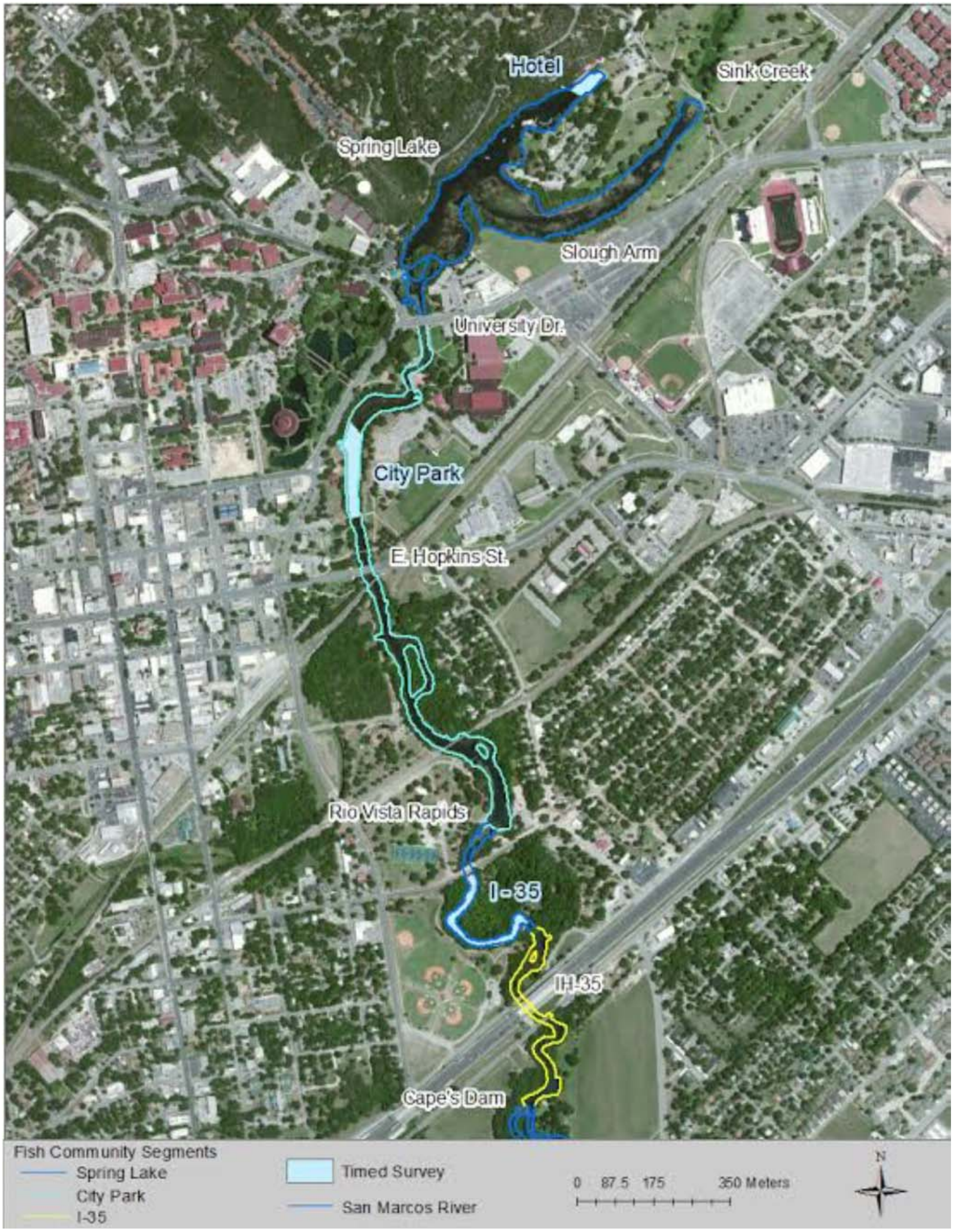

FIGURE 4-4 Fish community sampling segments, and dip net timed survey sections (blue) for the Upper San Marcos River.
SOURCE: BIO-WEST (2014b).

FIGURE 4-5 Fish community sampling segments, and dip net timed survey sections (blue) for the Lower San Marcos River.
SOURCE: BIO-WEST (2014b).

Biomonitoring Methods

Texas Wild Rice and Submersed Aquatic Vegetation

San Marcos. Sampling of submersed aquatic vegetation (SAV) in the San Marcos system began in 2000 with two index reaches; a third reach, Spring Lake, was added soon after. The full-system aquatic vegetation mapping was added to periodically assess how representative the sample reaches are and to characterize the native and nonnative species distribution throughout the entire river. The current sampling design for TWR and SAV are (1) full-system mapping of Texas wild rice annually, (2) full-system mapping of SAV once every five years, and (3) sampling of SAV and Texas wild rice in three index reaches twice a year.

In terms of methods, the SAV mapping was conducted using a global positioning system (GPS) with real-time differential correction capable of sub-meter accuracy. The aquatic vegetation was identified and mapped by gathering coordinates (creating polygons) while maneuvering around the perimeter of each vegetation type at the water's surface in a kayak. In 2013 a new protocol assessing all aquatic vegetation species was introduced; instead of mapping dominant vegetation only (as in previous years), all vegetation species in mixed stands are assigned a percent cover. This percent is multiplied by the total area of the stand to get an accurate surface area of that particular species.

The biomonitoring program also includes physical observations of Texas wild rice. When sampling began in 2000, Texas wild rice stands throughout the San Marcos River were assessed and documented as being in "vulnerable" areas if they possessed one or more of the following characteristics:

(1) occurred in shallow water (<0.5 feet),
(2) revealed extreme root exposure because of substrate scouring, or
(3) generally appeared to be in poor condition.

The areal coverage of Texas wild rice stands in vulnerable locations were determined in 2013 by GPS mapping (described above) in most instances, with some smaller stands measured using maximum length and maximum width. The length measurement was taken at the water surface parallel to streamflow and included the distance between the bases of the roots to the tip of the longest leaf. The width was measured at the widest point perpendicular to the stream current (this usually did not include roots). The length and width measurements were used to calculate the area of each stand according to a method used by the Texas Parks and Wildlife Department.

Comal River. The same sampling technique described above for the San Marcos River was employed to map the SAV in the Comal River system. In 2013, a comprehensive river system sampling study was conducted in January-February, as well as the annual spring-fall sampling in the sample reaches. A third sampling effort was conducted during the critical low flow period in August.

Overall the sampling technique for gathering the percent cover of SAV in the two spring systems is adequate. A study to determine the representativeness of the current reach sampling was not uniformly successful, in that some index reaches mimicked the total river section while

others did not (BIO-WEST, 2014a). For example, in the Upper Spring Run, reach coverage in 2013 was comparable to that of the total run, but the average reach coverage over the 2001–2013 time period was not. In the Old Channel and New Channel reaches, data from the index reaches measured either in 2013 or over the 2001–2013 time period did not follow the actual SAV species coverage in the entire section measured in 2013; however, in Landa Lake the data matched for both time periods. Because of the apparent sensitivity and variable response of SAV to flow conditions, particularly in the Comal River, it would be best to either sample the total river more frequently than every five years or increase and/or randomize the sampling locations if a more accurate representation of SAV throughout the river is desired.

The above sampling methods do not include data needed for the SAV modeling efforts, i.e., plant biomass. For dominant species and species specifically used in the modeling process, biomass data should be collected annually (and may need to be collected multiple times during the growing season to estimate specific growth rates) to validate the percent cover data and to provide accurate data for the SAV model.

Fountain Darter

The fountain darter sampling uses an ad-hoc design whose gear, frequency, and locations are tailored to the index reaches where responses are expected and coordinated with locations used for other aspects of the biomonitoring. Such a design is valid and likely appropriate for this type of small system and when designed by investigators who know the system, which is the case here. The key to a valid ad-hoc design is that the collected data on fountain darter are appropriately interpreted. It is possible that the EAA or others may want to use data on fountain darter densities in the index reaches to make statements about the total abundance of fountain darters in the Comal and San Marcos systems. Because the index reaches are not representative (see previous discussion), careful consideration should be given to how trends in darter density and local (reach-specific) abundance based on the index reaches will be interpreted, what constitutes a significant drop or increase (magnitude and duration), and whether and how to scale up to determine the status of the total population.

The biomonitoring for darter has, and should continue to be, modified over time in order to adopt new sampling methods and adapt to changing conditions. The key to effective modifications, such as changing sampling locations, gear, or frequency, is to ensure a sufficiently long enough period during which the old and new methods co-occur. Ensuring adequate overlap in time of the old and new sampling methods, and even maintenance of low-density sampling locations or old methods, is needed to ensure easy bridging between data based on the new and old methods and thus maintain the integrity of the accumulated time series. The need for overlapping sampling has been recognized (e.g., presence/absence with random versus fixed stations, BIO-WEST, 2014b, p.15); however, data analyses and more rigorous evaluation need to be performed to support the extent to which the overlap is needed. Interpreting the data (from either index sites or system-wide) requires a very clean time series that is not interrupted or confounded with changes in the sampling.

It would also be timely to consider special studies related to the use of index sites to indicate fountain darter trends. These special studies could be performed for a limited time to confirm or even improve the interpretation of the standard year-to-year monitoring. One set of

studies could be designed to address the representativeness of the index reaches, and to benchmark the degree of uncertainty when index information is extrapolated to the regional or system level. The study would likely use a stratified random design (to avoid too much sampling in very low density locations), and last for several years. Analyses to assess the representativeness of the index reach sampling after each year of data collection would provide valuable information on the sampling needed to fully assess the uncertainty in scaling over a range of environmental conditions. Another study could confirm the present thinking that underlies the sampling locations about where darters are located and absent, and thus where sampling is not needed. Information that darters are, indeed, not found or only found in very low densities in certain habitats or locations during specific seasons would increase the confidence in the sampling results. Third, a common issue with most fish sampling is how gear selectivity and avoidance behavior, both of which can vary with conditions and habitat, affect the collected data and extrapolation of the data to broader scales (sample site to river reaches to the whole system). In this system a variety of gear is used to sample fountain darter. Some additional information on gear selectivity would be helpful for data interpretation and extrapolation and to ensure that issues about gear efficiency are not confounding results. The results of the special studies discussed above may not lead to major changes to the monitoring, but such special studies are reassuring and often yield supporting information that gets called upon as others examine, interpret, and possibly challenge the monitoring data.

Comal Springs Riffle Beetle

As part of the HCP, invertebrates in the Comal system, including the Comal Springs riffle beetle (CSRB), Peck's cave amphipod, and Comal Springs dryopid beetle, are sampled using two methods. First, drift nets are used at three spring locations twice a year to measure accumulated organisms (see yellow squares in Figure 4-2), with the listed species being returned to their spring of origin after enumeration. Second, cotton lures are used to attract CSRB twice a year and during critical low flows (including the drought conditions of 2013). These lures are placed at ten springs in each of three locations: Spring Run 3, along the western shoreline of Landa Lake, and near Spring Island (see Figure 4-2 in EARIP, 2012). These sampling efforts are an increase over what occurred during the EAA Variable Flow Study (BIO-WEST, 2007), in which populations of the CSRB were monitored at three spring upwelling regions of Landa Lake over six years. Taken together there are about ten years of CSRB data from the Comal system, including during drought conditions.

The data presented in the HCP show that the populations of the CSRB were stable from 2004 to 2010 (EARIP, 2012, Table 4-8). However, in 2013 severe drought conditions substantially affected the Comal Spring system including the threatened invertebrate and salamander populations. During that drought, several of the springs that serve as habitat for the CSRB completely dried up for variable amounts of time. The populations of CSRB as measured with cotton lures were reported to be below their historical averages, which was attributed to the prolonged drought and reductions in spring seep flows that either affected the populations directly or altered sedimentation rates in a way that reduced CSRB counts (BIO-WEST, 2014a). However, a long-term trend analysis from the BIO-WEST report could find no statistical relationship between total system discharge or individual spring discharge and the average number of beetles collected per lure. There could be many reasons for this, including limitations

with the cotton lure method for evaluating CSRB populations, the possibility that populations are not responding to flow at those scales of measurement, or potential lag times where the populations may be responding to previous flow conditions and not the conditions noted on the day of sampling. It also calls into question the representativeness of the sampling and highlights the lack of life history information on this species, which makes it even more difficult to understand the meaning of changes in CSRB lure counts.

Interestingly, the biomonitoring conducted during 2013 found that the Texas wild rice and fountain darter populations were unaffected by the drought conditions, while the CSRB, Comal Springs salamander, and Peck's Cave amphipod all were negatively affected. These short-term responses to drought level flows suggest that the CSRB may be the most sensitive of the listed species, warranting more thorough investigations to better understand the distribution and life history of this species and the other threatened invertebrates (e.g., Comal Spring dryopid beetle and Peck's Cave amphipod) within the Comal Springs and San Marcos River systems. A study to better understand the flow tolerances of the CSRB is part of the 2014 Applied Research Program (see Chapter 5), but as discussed below, this only scratches the surface of information needs for this species.

The main knowledge gap for CSRB is the lack of life history information, including the true densities of immature (larval), pupal, and adult life stages throughout the year; growth rates of the life stages; how many generations occur each year; how fast the life cycle proceeds; the synchrony or asynchrony of cohorts; or how the life cycle and other life history attributes like fecundity might be affected by changing flow or sediment conditions. It is possible that existing, historical data could be analyzed in a way to make life history inferences important for understanding population responses to environmental change. For instance, in the overall trend analyses of the 2013 biomonitoring report (BIO-WEST, 2014a), only adult beetles were considered; if there were similar data on larvae or pupae, some inferential life history information could be derived. Monthly quantitative sampling (surveys or some form of areal counts for density estimates) would also provide this information, as suggested by Bowles et al. (2003).

Measuring CSRB distribution should be a high priority, using a randomized or stratified randomized approach throughout Lake Landa, Spring Island and other areas of potential habitat. One Applied Research project proposed to do something similar to this (in addition to refining CSRB collecting methods), titled *Study to Establish Comal Springs Riffle Beetle Baseline Population Distribution and Refine Riffle Beetle Collection Methods: Proposal No. 125-13-HCP*. The study began in 2014 and should yield promising information important to understanding the broader ecological distribution of this beetle.

A major issue is the difficulty in quantifying the habitat of the CSRB and the other threatened invertebrates and salamanders, in terms of determining its areal coverage. The known primary habitats of these species are spring outflow seeps and subterranean corridors. A map of the current and potential habitat of these species is currently unavailable, but would be important for including the CSRB in future modeling efforts and identifying changes in habitat quality in response to such stressors as low flow and siltation. Furthermore, it is difficult to conduct quantitative sampling of organism density in spring outflow seeps and subterranean corridors, as described in BIO-WEST (2002), which is why the cotton lure method has been used and why the HCP goals for CSRB include maintaining silt-free spring rock and pebble substrates rather than more quantitative measures.

New methods for quantifying CSRB should be considered. For instance, much like the quantitative methods employed in the monitoring of the fountain darter and salamander populations using standardized visual surveys, the CSRB populations could be evaluated in a similar way using SCUBA or snorkel and additional hand-held magnifying tools while carefully and deliberately turning over rocks and removing and assessing vegetation for specimens in a defined area. Additionally, hyporheic pumping, freeze-coring or the use of colonization pots/baskets approaches could be modified from known methods (e.g., Scarsbrook and Halliday, 2002) to provide more quantitative CSRB counts on a monthly basis for the Comal system. If new quantitative sampling methods for the CSRB could be developed, then comparative studies could be conducted to determine how well the cotton lure approach represents densities. This information would be valuable for retrospective evaluations of the CSRB over the last ten years when the cotton lure method was used to monitor population changes. New techniques for sampling CSRB may be difficult to undertake and may require additional funding, but are nonetheless important considerations if this listed species turns out to be one of the more sensitive species in these systems. All of this is dependent on permit take limits that should be considered with all future research on this and the other listed species.

As part of the Applied Research Program, the HCP has proposed future laboratory experiments, using *Microcylloepus pusillus* (Elmidae) as a surrogate species, to better understand how physical and chemical changes that may occur with lower spring velocities will impact CSRB survival. These studies could be reasonable to better describe the tolerances of CSRB and mechanisms for its survival under low flows, but only if life history information on CSRB confirms that *M. pusillus* may effectively be used in monitoring as a surrogate (i.e., they should have similar life cycles, abiotic tolerances, habitat and food requirements, predators, diseases).

Finally, while one of the major objectives of the HCP is to limit sedimentation effects on CSRB and other species habitat through riparian restoration efforts, there seems to be no documentation on how these efforts will be measured for effectiveness and sustainability.

Even less is understood about other threatened invertebrates such as the subterranean Comal Spring dryopid beetle and Peck's Cave amphipod, and there have been fewer monitoring efforts. Additional life history and distribution studies are needed for these rare species as well, and a new approach to identifying and quantifying common habitat of these invertebrates warrants additional consideration, investigation, and resource investment.

As part of the Applied Research Program, a focused project on testing how well the CSRB acts as an indicator of the other threatened organisms is critical to a more comprehensive plan that conserves and protects all listed species in these aquifer-driven systems. Since the CSRB is thought to be restricted to springs and seeps throughout the Comal River system, a first step in testing CSRB as a multi-species indicator would be to quantify changes in the CSRB populations with matched population assessments of the other species in or near the springs and seeps. This will not be an easy task, and it will require considerable planning and the creative development of non-destructive approaches for sampling springs, adjacent habitat, and the hyporheos. However, visual survey approaches like those already being employed for the fountain darter and spring salamanders show promise for this kind of research. Additionally, recent research activity related to eDNA may offer a way to assess these more cryptic, difficult-to-sample, and rare species (Jerde et al., 2011; Thomsen et al., 2012). An eDNA approach could be evaluated for both the CSRB populations and the other listed animals and could serve as a high priority Applied Research project.

Benthic Macroinvertebrate Communities

Compared to other sampling programs, macroinvertebrate sampling has a much shorter history. Macroinvertebrate community sampling commenced in 2013 in the index reaches of both the Comal and San Marcos River systems as a way to assess fountain darter food sources. It is scheduled to occur twice a year and rely on the Triple H sampling method (BIO-WEST, 2014a). The Committee recommends that the macroinvertebrate surveys be expanded to habitats that are not currently being evaluated to provide information on the overall health of the aquatic ecosystem, similar to what is done for surface waters throughout the United States as part of national bioassessment programs (Barbour et al., 1999; Rosenberg and Resh, 1993). Standard bioassessment approaches for flowing water habitats are particularly useful in situations where there is a lack of information on the dominant factors affecting individual species or on how multiple species are connected, much like the Comal and San Marcos River systems. To carry this out, a stratified randomized approach using the existing vegetation mapping could be used to identify the top three or four predominant habitat types; then for each habitat, quarterly or biannual sampling could commence to determine the health of the overall macroinvertebrate community using standard EPA biomonitoring protocols. Standard macroinvertebrate biomonitoring programs are common throughout the United States and could easily be accomplished by the current expertise of the contractors of the EAA.

WATER QUALITY MONITORING PROGRAM

Water quality monitoring has occurred at various locations in the Comal and San Marcos springs and river systems for more than ten years. The water quality monitoring program consists of five distinct parts: groundwater, surface water, stormwater, sediments, and continuous measurement (see Tables 4-3 and 4-4 for details). Groundwater is sampled at selected spring sites four times per year and more frequently under low flow conditions. Surface water and stormwater are each sampled twice per year, with stormwater samples timed to coincide with major rain events. Sediment samples are taken once per year from the same locations as surface water samples. Continuous measurements of water temperature, dissolved oxygen, pH, turbidity, and specific conductance are made at 15-minute intervals using a multiparameter sonde. With a few minor exceptions, samples from groundwater, surface water, stormwater, and sediments are analyzed for the same comprehensive set of inorganic and organic constituents, including major anions and cations, nutrients, alkalinity, organic carbon, volatile and semivolatile organic compounds, pesticides and herbicides, metals, and bacteria (see Appendices A and B in EAA, 2013).

Sample locations differ depending on the type of sampling, and while there is location overlap among sampling type, no single location is the site for surface water, storm water, sediment, and continuous measurement (Tables 4-3 and 4-4). Similar to the biomonitoring program, sampling locations were not selected randomly and should be considered index sites that are not necessarily representative of the entire river system. In situations where it is desirable to extrapolate to the entire system to characterize a particular parameter, it is important to evaluate the degree to which the current monitoring locations are representative or to develop a randomized sampling design that can be used to provide representative samples.

Table 4-3 Comal Springs Water Quality Monitoring Plan for 2014

Location	Groundwater	Surface Water	Stormwater	Sediment	Sonde
Spring 1	4x/year* for complete set^				
Spring 3	4x/year* for complete set^				15 minute intervals for temperature, DO, pH, turbidity, Sp. Cond.
Spring 7	4x/year* for complete set^				15 minute intervals for temperature, DO, pH, turbidity, Sp. Cond.
Upper Springs (near Bleiders Creek)		2x/year for constituents listed in Appendix A	2 storms/year for constituents listed in Appendix A	1x/year for constituents listed in Appendix B	
Upper Landa Lake (near Spring Island)		2x/year for constituents listed in Appendix A		1x/year for constituents listed in Appendix B	
Lower Landa Lake (above outfalls)		2x/year for constituents listed in Appendix A		1x/year for constituents listed in Appendix B	
Upper Old Channel (Elizabeth Street)		2x/year for constituents listed in Appendix A	2 storms/year for constituents listed in Appendix A	1x/year for constituents listed in Appendix B	
USGS Gauge (above San Antonio Street Bridge		2x/year for constituents listed in Appendix A		1x/year for constituents listed in Appendix B	
New Channel (below confluence with Dry Comal Creek)			2 storms/year for constituents listed in Appendix A		15 minute intervals for temperature, DO, pH, turbidity, Sp. Cond.
Lower Old Channel (above Hinman Island)			2 storms/year for constituents listed in Appendix A		
Comal River (above confluence with Guadalupe River)			2 storms/year for constituents listed in Appendix A		

*Monthly sampling if San Antonio Pool critical period triggers have been reached
^Complete set: DO, pH, conductivity, temperature, alkalinity, cations, anions, nutrients, metals, VOCs SVOCs, herbicides, pesticides, bacteria, TOC, PCBs, and phosphorous.
Appendix A and B refer to EAA, 2013

Table 4-4 San Marcos Springs Water Quality Monitoring Plan for 2014

Location	Groundwater	Surface Water	Stormwater	Sediment	Sonde
Deep Spring	4x/year* for complete set^				
Hotel Spring	4x/year* for complete set^				
Sink Creek		2x/year for constituents listed in Appendix A	2 storms/year for constituents listed in Appendix A	1x/year for constituents listed in App. B	
Spring Lake		2x/year for constituents listed in Appendix A		1x/year for constituents listed in App. B	
Sessoms Creek		2x/year for constituents listed in Appendix A	2 storms/year for constituents listed in Appendix A	1x/year for constituents listed in Appendix B	
City Park		2x/year for constituents listed in Appendix A		1x/year for constituents listed in Appendix B	
Rio Vista Dam		2x/year for constituents listed in Appendix A		1x/year for constituents listed in Appendix B	15 min. for temp, DO, pH, turbidity, Sp. Cond.
Dog Beach Outflow			2 storms/year for constituents listed in Appendix A		
Hopkins Street Outflow			2 storms/year for constituents listed in Appendix A		
Purgatory Creek			2 storms/year for constituents listed in Appendix A		
I-35 reach		2x/year for constituents listed in Appendix A	2 storms/year for constituents listed in Appendix A	1x/year for constituents listed in App. B	
Capes Dam		2x/year for constituents listed in Appendix A		1x/year for constituents listed in App. B	
USGS Gauging Station					15 min. for temp, DO, pH, turbidity, Sp. Cond.
Willow Creek			2 storms/year for constituents listed in Appendix A		

*Weekly sampling if San Marcos Springs <50 cfs; additional parameters weekly if <30 cfs.
^Complete set: DO, pH, conductivity, temperature, alkalinity, cations, anions, nutrients, metals, VOCs SVOCs, herbicides, pesticides, bacteria, TOC, PCBs, and phosphorous.
Appendix A and B refer to EAA, 2013

Contaminant Sampling

A long list of organic and inorganic contaminants—from pesticides to metals—is being sampled to assess the current degree of contaminant load (see Appendices A and B of EAA, 2013 for the parameters and sampling protocols). The parameters that have been selected represent a broad set of contaminants and are generally appropriate to define baseline conditions and to identify potential impairments of the springs and river systems. However, the parameters are focused on industrial and commercial contaminants (e.g., VOCs, SVOCs, PCBs) that may not represent the most substantial risks for the springs. The potential for other contaminants, particularly those associated with urbanization and residential use, should be evaluated and incorporated into the sampling program. In particular, household chemicals, personal care products, and residential herbicides should be evaluated for their potential to be introduced into the springs and river systems.

The sampling is widely dispersed; taking the regular surface water sampling and the augmented stormwater sampling into account, contaminants are measured in unfiltered samples from 13 and 11 locations in the San Marcos and Comal Springs and river systems, respectively. Baseline sampling for the current list of constituents is appropriate, but if no significant concentrations are observed, further sampling for these parameters should be eliminated or conducted at reduced frequency and/or at fewer locations in each spring and river system, as planned (personal communication, Ed Oborny, BIO-WEST, 2014). In particular, the number of contaminant sampling locations should be reduced and effort reallocated to sampling additional storm events, should they occur. Because stream flow during storm events is likely to be high, fewer sites somewhat downstream could be monitored to get an integrated measurement. If contaminants show up in high concentration at that site, then further sampling at additional locations for that contaminant could be done in follow-up studies to pinpoint potential sources.

Methods for stormwater event sampling require further analysis and may need to include additional parameters for appropriate characterization. In particular, it may be appropriate to employ size-segregated stormwater analyses, recognizing that the fate and transport of any stormwater contaminant are closely related to particle size. Coarse particles tend to settle rapidly and will lead to near-source impacts while fine particles may be rapidly transported out of the spring-fed rivers. Conversely, fine particle-associated contaminants may exhibit greater bioavailability leading to exposure and risks of the target species. If loading from stormwater is found to be of potential concern, studies addressing the availability and fate of contaminants as a function of particle size will need to be addressed. Currently, the stormwater sampling is done manually, but two alternative sampling methods for contaminants are being considered—Gore passive samplers and automated sampling using ISCO samplers. An initial review suggests that both methods may be appropriate if the baseline sampling identifies potential concerns. Neither approach seems to be consistent with the preliminary nature of the problem identification phase that currently defines the water quality sampling program, but one or both would be needed to quantify contaminants introduced by stormwater events.

Nutrient Monitoring

Although the list of water quality parameters monitored is generally appropriate, the Committee has concerns about the monitoring of nutrients, especially phosphorus. Nutrient

loading is typically an important driver of biological processes in aquatic ecosystems, especially in agricultural and urban watersheds. In many cases, the type, abundance, and distribution of algae and aquatic macrophytes is directly influenced by the nutrient regime of the water body. Because nutrient loading is typically influenced by weather, land use, land cover, and stream canopy cover, it can and does change over time in many systems. In many freshwater systems phosphorus is a limiting nutrient (Elser et al., 2007; Schindler, 1977), and because nitrogen is generally abundant in the San Marcos and Comal spring and river systems, it is likely (but apparently still not known with certainty) that phosphorus is limiting in these systems.

The reported detection limits for soluble reactive and total phosphorus measurements are 50 and 20 micrograms per liter, respectively, while the detection limits for nitrogen species are are 50 micrograms per liter for NO_3/NO_2 and 500 micrograms per liter for total nitrogen (Table 1 in BIO-WEST, 2014a and b). These values are above the level at which significant impairment of water quality can occur. Therefore, important changes or trends in nutrient loading to the spring and river systems could be occurring without detection. The Committee recommends that the method for phosphorus measurement be changed such that the detection limit is 2 micrograms per liter. This level of detection is standard in most non-wastewater monitoring of phosphorus, it is reasonable, and it would be helpful in detecting whether P concentrations are changing over time in a way that is meaningful to the ecology of the springs and rivers. The detection limits for NO_3/NO_2 and total nitrogen should be reduced to 10 and 50 micrograms/liter, respectively.

If total phosphorus concentrations above a few micrograms per liter are indeed present in the spring and river systems, the EAA should consider initiating a research project to understand the relationship between nutrient concentrations and the abundance of algae and macrophytes. Such a study should consider all possible sources of water column nutrients including both the sediments as well as direct runoff from the watershed.

CONCLUSIONS AND RECOMMENDATIONS

The extensive monitoring of physical, chemical, and biological characteristics of the Comal and San Marcos spring and river systems under the Edwards Aquifer Authority Variable Flow Study from 2000-2012 and since 2013 under the HCP has provided a wealth of information upon which to base a long-term monitoring program. Choices of variables to measure and the sampling methods, locations, and frequencies were based largely on previous experience and knowledge. While in general the Committee found the monitoring programs to be strong, it also identified areas for improvement. The strengths and weaknesses are highlighted below.

The biomonitoring and water quality monitoring programs are generally well designed, comprehensive, and likely to be effective in providing information to meet the objectives of the HCP. The design and implementation of the monitoring programs was developed using expert knowledge and experience gained over more than a decade of intensive sampling and study. This prior knowledge has proved invaluable in developing the current sampling design. Monitoring of index reaches needs to continue in order to assess trends and build on existing databases.

The sampling programs do not provide a clear mechanism to scale results to the entire spring and reach system. If the EAA finds it is necessary to provide system-wide estimates of population densities of target species rather than relying on trends and index stations, it will need to invoke special studies or conduct sampling using randomization techniques. For example, a special study to determine the representativeness of the fountain darter trends estimated in index reaches would sample for darters very broadly and then examine the uncertainty associated with using the index information to infer densities and abundances at broader scales (groups of reaches and system-wide).

The biomonitoring and water quality monitoring programs are only loosely integrated. Both programs measure water temperature, dissolved oxygen, and nutrients. Both programs use multiparameter sondes for continuous measurements, but at different frequencies and perhaps with different calibration protocols. Surface water and sediment sampling locations are co-located, but there appears to be no single location that is sampled for surface water, storm water, sediment, and continuous measurement by sonde. Water quality monitoring occurs at some, but not all, of the biomonitoring sampling locations (except for the limited water quality monitoring that is done as part of the biomonitoring program). Furthermore, annual reports for the two monitoring programs are produced independently. It is unclear whether there is a process for integrating information across the two monitoring programs in order to provide a full assessment of biological and environmental conditions. For example, it was confusing that data for phosphorus was found in the biomonitoring report, but not the water quality report.

Increased coordination and integration of the biomonitoring and water quality monitoring activities is needed. For example, whenever possible sampling sites for water quality and biomonitoring should be co-located to allow better integration and synthetic analyses.

Enhanced sampling for nutrients is recommended. The presence of annual algal blooms and the importance of aquatic macrophytes in structuring fish and macroinvertebrate communities suggest that nutrient loading plays an important role in the spring and river systems. As described in the chapter, the detection level of 50 micrograms/liter for soluble reactive phosphorus, 50 micrograms/liter for NO_3/NO_2, and 500 micrograms/liter for total nitrogen are so high that significant changes in nutrient concentrations could go undetected. If the detection limits for phosphorus species, NO_3/NO_2, and total nitrogen were reduced to 2, 10, and 50 micrograms/liter, respectively, by changing analytical methods, this would enable identification of nutrient concerns in both spring systems.

It is expected that nutrients and other urban background contaminants may be more important than many of the specific toxins that are currently included in the sampling program. The planned elimination of many of these parameters after one or two initial rounds of sampling if significant detections are not observed is supported by the Committee. As with phosphorous, it is important that the methods used allow reliable detection of any constituent at potential levels of concern before any decision is made to eliminate that parameter.

New quantitative sampling methods are needed for the CSRB to complement and improve upon the cotton lure approach. At the same time, a large-scale stratified random survey of the potential habitat available in both systems would provide more robust data on how flow variation or sedimentation affects the habitat and thus population numbers of CSRB. The comprehensive survey of CSRB distribution proposed as part of the Applied Research Program should be given high priority.

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5

Applied Research Program

As Chapter 3 makes apparent, there is a great deal of knowledge regarding fountain darters and Texas wild rice within the EAA and their collaborators, but similar knowledge is lacking for the Comal Springs riffle beetle (CSRB) and most of the other covered species. Critical to the recovery and protection of all aquifer species is knowledge of the species-specific demography and ecology, including knowledge of natural population fluctuations. It is for this reason that the Habitat Conservation Plan (HCP) has an Applied Research Program, the intent of which is to "better understand the ecological dynamics of the Comal (and San Marcos) system(s), particularly under low flow conditions."

The Applied Research Program has several goals. These are to (1) fill gaps in knowledge about particular listed species, (2) increase understanding of key processes that affect their population dynamics, and (3) provide data and information that can be used to parameterize and validate the ecological models. The overall goal of the program is to generate useful information during Phase 1 to be able to make well-informed decisions about the overall direction of the HCP during Phase 2.

Based on the projects funded to date and the composition of the EAA's Science Committee, which plays an advisory role in the Applied Research Program, it is evident that the Applied Research Program was created to address primarily ecological questions rather than hydrogeologic questions. This is partly because the EAA already has an Aquifer Science Research Program in place to explore hydrogeologic and hydrologic modeling issues that may arise during implementation of the HCP (although it should be noted that this program is NOT funded through the HCP). Accordingly, the Applied Research Program focuses on the listed species and the information necessary to adequately assess and model those species under both normal and critical drought conditions. The membership of the Science Committee, which reviews proposals for the Applied Research Program, is dominated by members with ecological expertise, with only two of the ten members being hydrologists.

Even given the focus on ecological questions, however, the Applied Research Program could be significantly restructured to better identify and then fill gaps in understanding of the Edwards Aquifer system. Such restructuring would help to ensure that the limited funds available for the Applied Research Program target priority research needs to support the EAA's ecological modeling efforts and the success of the HCP more generally.

With that larger restructuring need in mind, the following sections separately consider all of the projects that have been funded to date, organized by organism; new studies that might be part of the Applied Research Program; and the committee's conclusions about the current Applied Research Program including how it is structured and its recommendations for

restructuring. The intent is to steer the program in the direction that will be most useful for furthering basic understanding of ecological processes and modeling.

CURRENT PROJECTS

The following is a brief assessment of the 2013, 2014, and 2015 projects that make up the Applied Research Program, organized by species. Rather than provide an exhaustive description, which can be found in EAA documents, this section is meant to evaluate whether these projects meet an important need, such as filling a knowledge gap or being relevant to either the new ecological models or to the existing habitat suitability analyses. Later in the chapter, new project topics are described that should be considered for inclusion.

In general, the Committee notes that it is difficult to fully evaluate these projects until final reports are available because the information on methods and anticipated analyses in the proposals is very limited. Some of the proposals for the 2014 and 2015 studies had only two to three pages (out of almost 100) on methods, and very few discussed how the data would be analyzed. In contrast, these proposals had long and repetitive statements of investigator qualifications. Furthermore, many of the proposals listed a literature review as a task to be done. Literature reviews are usually not part of an applied research project, but rather are done during preparation of the proposal to demonstrate that the proposal authors have a strong knowledge of the background information necessary to develop suitable hypotheses and propose appropriate methods for testing them. Finally, some proposals contained such statements as: "Specific hypotheses will be prioritized during the full literature review process." It is very difficult to evaluate proposals when the hypotheses to be tested and the methods are not specified in detail. Without such basic information, it is not clear how one knows the appropriate methods to use, and whether any proposed methods would yield useful results. It should be noted that the final reports received to date are well written, but that does not help for those projects which do not yet have final reports submitted.

Fountain Darter

There are four major research themes related to fountain darter that directly benefit from the Applied Research Program: better interpretation of the monitoring data, refinement of the effects of flow on darter, increased understanding of habitat use by darter (and potentially suitability functions), and generation of data and information for darter population modeling. We examined five darter-centric studies that have been or are planned as part of the Applied Research Program, as listed in Table 5-1. All of these studies have merit for attempting to address valid scientific questions. Whether these studies have met an important need for the HCP is examined by looking at their relevance to one or more of the research themes.

Study 1 involves a food source of fountain darter, while Studies 2 and 4 focused on fountain darter movement and predation by two fountain darter predators in vegetated versus non-vegetated habitats. Thus, these three studies could provide useful information on habitat utilization by fountain darters. Study 1 has been completed and established a critical thermal maximum (CTM) of 37.89 °C for *Hyalella azteca* taken directly from the Comal River. Nonetheless, it is likely that the tolerance of this species when confronted with multiple stressors

could be considerably less than the CTM. The results would be strengthened by additional information about (1) the effects of temperatures between 28 and 34 ^{o}C, (2) how important and limiting *Hyalella* is as a food source for fountain darter, and (3) how different spring flows relate to the temperatures tested (both magnitude and duration) under field conditions. It is not clear how the tested temperature would be expected to occur in the field, and then what percent of *Hyalella* would need to be affected to actually have a reduced food (and resulting slowed growth) effect on fountain darter. The overarching issue for these three projects (#1, 2, and 4) is the need to determine what fountain darter eat by life stage and in different habitats, and how changes in prey availability affect their growth and reproduction.

TABLE 5-1 Fountain Darter Applied Research Projects

Study Title	**Year**	**Objective**
1. Fountain Darter Food Source Study to Determine the CTM of *Hyalella Azteca*	2013	To determine the critical thermal maximum (CTM) of *Hyalella azteca*, a supposed fountain darter food source. Final report completed (BIO-WEST and Baylor University, 2013).
2. Effects of Vegetation Decay and Water Quality Deterioration on Fountain Darter Movement	2014	To describe fountain darter movement as a function of water quality and vegetation decay using fluorescent tags. Final report completed (BIO-WEST, 2014a).
3. Effects of Low-Flow on Fountain Darter Fecundity	2014	To determine if changes in physical habitats, especially low-growing and dense vegetation, will reduce the reproductive readiness and success of the fountain darter. Final report completed (Texas State University and BIO-WEST, 2014a).
4. Effects of Predation on Fountain Darter Population Size at Various Flow Rates	2014	To determine if flow conditions may cause different relationships between predator and prey and habitat utilization. Final report completed (Texas State University and BIO-WEST, 2014b).
5. Algae Dynamics and Dissolved Oxygen Depletion Study	2015	To better understand the cause and effects of excessive algal blooms on bryophytes in the Upper Spring Run and Landa Lake sections of the Comal River. Proposal available (BIO-WEST Project team, 2014a).

Study 2 examined movement patterns of fountain darters, with some observations under low flow and poor water quality conditions. The idea of using fluorescent tags to infer spatial movement patterns is excellent and useful for general understanding of fountain darter habitat for the ecological model. The analysis of the data could have been improved. For example, how to treat “lost” or non-recovered tags so as to not bias the movement information is always difficult. Also, the effect of low flow was not sufficient to be quantified. A follow-up study on movement should be considered, perhaps using tags that provide near-continuous information on the locations and temperatures experienced by the individually tagged fish.

Study 3 focused on flow (and vegetation) effects on fountain darter fecundity. If the sole justification for Study 3 was to resolve issues related to flow effects on darter, then those arguments should be strengthened. The study provided some basic and useful information on the timing of spawning based on observed gonadosomatic index (GSI) values; however, GSI cannot be directly related to batch frequency and size, which are needed in the modeling to generate egg production for individuals and the population. Neither the effects of flow nor vegetation type on

fecundity were quantified, either because there is truly no linkage or because the effect would be difficult to detect. That is, flow and vegetation may act indirectly on reproduction (e.g., via food and then growth) and it is not clear over what time period an individual's habitat residency or recent past flows affect the energy devoted to reproduction (GSI) and batch development and release.

The predation study (Study 4) used an interesting progression of lab, pond, and field enclosures to examine predation rates. Oddly, Study 4 included "flow" in the proposal title but not in the proposal methods nor in the final report. Using single and paired predator species with and without vegetation seems promising, if the methodological scaling issues can be solved. Such lab and enclosure studies are notorious for having difficulties with predator-prey interactions because of unrealistic spatial and temporal scales (Carpenter, 1996, 1999; Drenner and Mazumder, 1999). Predation is based, among other factors, on the encounter rates between predators and their prey. Creating protective habitat (vegetation in this case) in small systems and failing to replicate aspects of the environment related to predator behavior and prey avoidance of predators can result in a distorted view of the role of predation. It is not clear that the results of the study (that predators are additive and that vegetation has no effect) will be generalizable.

Information about Study 5 (algal-bryophyte dynamics) comes from a 2015 proposal only, and thus is difficult to evaluate. In theory, this could be an important study for filling a knowledge gap about a suspected problem previously ignored. However, is not clear based on the proposal that the methods can generate useful enough information to justify this study over others. The chain of events provided as the rationale for the study is quite complicated (low flow → algal growth → bryophytes die → macrophytes decay → less darter habitat → negative effects on darter growth or mortality). The first few steps may be elucidated by the study, but the latter are likely to be challenging.

Most of the project proposals include as justification relevance to the fountain darter ecological modeling, and this is highly likely given the involvement of the modelers with the study design. It would be useful for the proposals to further clarify what the outputs of each study will look like, and then how those will be incorporated into the modeling. The link between the study outputs and the modeling will either be for process formulation (e.g., flow effect on fecundity), calibration, validation, or bounding conditions in scenario analyses. In order to make this link, and thereby ensure the studies are well designed for use with the modeling, the details are critical. Vague statements about how "a study measures fecundity and that the model needs fecundity" are inadequate for justification and will inevitably lead to the ineffective use of the study results in the modeling. The final reports should state how the results will inform the process formulations of growth, reproduction, mortality, and movement of fountain darter, as well as model calibration and validation.

Modifications to these studies should be encouraged as the population model evolves and more details of the model are known. These modifications can also go in the other direction—that is, as study results become available they can influence how a process is represented in the model. For example, it may turn out that turbidity is a second order effect on feeding success, and thus the model does not need to include a turbidity effect on growth. Another example would be the movement information from Study 2 showing movement patterns and distances that require the simple movement algorithm in the model (e.g., move if too crowded or in poor habitat) to be changed in order to be capable of exhibiting the observed movement behaviors.

As recommended in Chapter 3, a full blown conceptual model would help to see where these studies fit into the big picture and determine whether they are of the highest priority. The studies for the fountain darter seem reasonable at a very general level, but are currently a loose collection of studies. They may turn out to be exactly what was needed to inform the ecological model. However, given the Committee's experience, this is unlikely without a more comprehensive evaluation of the link between the study methods and the modeling needs, some preliminary simulation results, and careful examination of what is critical to the modeling.

Submersed Aquatic Vegetation and Texas Wild Rice

The focus on submersed aquatic vegetation (SAV) in the HCP is a result of its importance as fountain darter habitat. The SAV modeling effort (described in Chapter 3) will include growth, recolonization and dispersal on a small gridded scale (0.25 m^2), relying on various calculations to estimate the extent of these processes. It is anticipated that many of the projects in the Applied Research Program applicable to SAV and Texas wild rice (listed in Table 5-2) will inform these modeling efforts.

In 2013 when the first set of studies was conducted, the SAV modeling effort was just beginning, such that the studies, which were preliminary, are not anticipated to have high relevance to the modeling. Nonetheless, some of the studies could provide potentially valuable data and information to the SAV model depending on how detailed it becomes. For example, the SAV model may be able to utilize information from Study #2 on the temperature thresholds for certain SAV to ensure their survival and continued growth, as well as information on their bicarbonate use (revealed in Study #3). The data on the relative growth rates for SAV species tested in Study #2 over a range of temperatures and CO_2 concentrations may also be useful. The results of the field vs. laboratory study were predictable (Murray and Kemp, 2008; Sanford et al., 2008; Carpenter, 1999) and may not be particularly valuable to the SAV modeling effort. Plants that grow under field conditions experience variables not found under laboratory conditions, such as competition among species, grazing, and uncontrollable physical parameters (e.g., temperature, turbidity), making plant growth under the two circumstances generally not comparable.

Only one Applied Research project in 2014 is related to SAV or Texas wild rice, and it was not officially part of the program. This is the project conducted at Baylor University to develop an empirical relationship for converting SAV biomass data to areal coverage data. The results from this study are critical for the SAV modeling because all of the data gathered on the Comal and San Marcos systems are percent cover data, while the likely SAV model will simulate plant biomass. As gathered from a verbal description at the Committee's second meeting and subsequent email communication, the methods for plant collection and laboratory analysis seem to fit with the goal of the study. Given that plants are collected intact, it would be an added benefit to collect plant length and stem counts. The grid size of 0.1 m^2 is standard for such measurements; however, it may be necessary to collect more than three samples if there is substantial variability when making the conversion between percent cover and biomass. The seasonal variability in plant biomass may not be captured if a species is only sampled once during the growing period. It should be noted that this study will not include Texas wild rice, probably because biomass sampling was considered to be too destructive. However, a stem

count to biomass regression could be made without destroying many plants, thereby allowing for an estimate of plant biomass through assessment of the number of Texas wild rice stems.

TABLE 5-2 Submersed Aquatic Vegetation and Texas Wild Rice Applied Research Projects

Study Title	Year	Objective
1. Field vs. Laboratory Study- comparison of the responses of three SAV	2013	Preliminary study to compare aquatic vegetation (*Ludwigia, Cabomba, and Sagittaria*) growth over time when conducted simultaneously in laboratory and in-situ experiments held at similar flow and water quality conditions. Final report available (BIO-WEST and Baylor University, 2013).
2. Vegetation Tolerance Studies A and B	2013	To evaluate the effects of elevated water temperatures in combination with low CO_2 and minimal flow on *Ludwigia, Cabomba, Vallisneria, and Riccia* in the lab and in ponds. Final report available (BIO-WEST and Baylor University, 2013).
3. pH Drift Study--Effects of HCO_3^- utilization by select SAV	2013	To determine which of the major submersed aquatic plant species of the Comal River are capable of utilizing HCO_3^- as a carbon source for photosynthesis. Final report available (BIO-WEST and Baylor University, 2013).
4. Converting SAV biomass to percent Areal Cover	2014	To develop an empirical relationship between vegetation percent cover and biomass. This will provide a realistic way to convert percent cover maps to levels of biomass present within the system. Final report available (Doyle et al., 2014).
5. *Ludwigia* Interference Plant Competition Study	2015	To evaluate *Ludwigia repens* growth competition and interference by *Hygrophila* sp. and *Hydrilla* sp. To better understand dispersal of *Ludwigi*a, and refine biological objectives. Proposal available (BIO-WEST Project Team, 2014b).
6. Suspended Sediment impacts on TWR (and Other SAV) and Macroinvertebrates	2015	To evaluate the timing and duration of suspended sediments in the San Marcos River, to evaluate suspended sediment impact on aquatic plant communities and on the aquatic macroinvertebrate community, and to produce information that will be useful for any eventual TWR model. Proposal available (Texas State University, 2014).

After receiving the final report in early December 2014, the Committee had the following additional thoughts. First, the researchers did not use the same method of estimating percent cover as is used in the biomonitoring program of the HCP; that is, two people made a visual assessment of percent cover, unlike the biomonitoring program which uses cameras and GPS. Second, the researchers developed regressions to relate biomass to plant cover that involved determining plant volume, which was estimated by multiplying the height of the plant by the percent cover of the sample. This does not take into account the actual volume displaced by the plant nor the structure of the plant (e.g., branching, linear structure, etc.). Without actual volume measurements, it is unclear how accurate the conversion from biomass to percent cover will be.

Two studies regarding SAV and Texas wild rice will be pursued in 2015. The first is an *in situ* plant competition study using *Ludwigia* and two nonnative species (*Hygrophila* and *Hydrilla verticillata*). *Ludwigia* is important for fountain darter habitat, and restoration efforts are underway to increase its presence in the springs. The study will assess *Ludwigia* growth

under varying competition from exotic SAV species. If the initial stem length and biomass of the planted fragments are measured, then the study could provide data to inform the SAV model (e.g., growth and biomass for *Ludwigia*). In addition, information from this study could be valuable to increase knowledge of competition among SAV species. The second study is an evaluation of suspended sediment timing and duration and its impacts on Texas wild rice (and other SAV) and macroinvertebrates in the San Marcos system. As mentioned in the section on fountain darter, this study will begin with a literature review, which is an odd approach since most proposals include a literature review by way of introduction and to establish justification for the proposed work. The proposal is contradictory in that it indicates one task to be developing methods for the study, but it also describes methods for collecting turbidity, invertebrates, SAV and other sampling procedures in detail. Information from this project could fill a knowledge gap for Texas wild rice (e.g., the effect of sediment on plant survival). Since turbidity is largely produced by recreation, the information obtained from this study could potentially inform the implementation of mitigation and minimization measures targeting Texas wild rice.

Comal Springs Riffle Beetle

The CSRB has been suggested as an indicator species for several other ESA-listed species, and so additional information on this beetle may prove critical to understanding how it and other populations can be modeled in response to flow rates and sedimentation. The Applied Research projects related to the CSRB were intended to fill some of the knowledge gaps about this species, and several of the projects have potential to provide important ecological information needed for future modeling efforts. However, additional considerations are warranted to better prioritize the projects to produce the most relevant information for modeling CSRB populations and habitat. The projects in the Applied Research Program applicable to CSRB are shown in Table 5-3.

The goal of Study #1 was to use a novel experimental design to create "spring upwelling" mesocosms that could shed light on CSRB survivorship inside of the springs during periods of low flow and flow cessation. The vertical flow regimes created in the mesocosms were intended to mimic periods of drought that have caused Comal Springs discharge to decrease to the point that spring upwellings no longer connect the subterranean and surface habitats that CSRB likely inhabit in the wild. The study suffered from several methodological setbacks that resulted in unexpected mortality of the CSRB, making their use in future Applied Research projects problematic. The main experiments were thus conducted with the surrogate *Heterelmis glabrai,* which was found to be substantially affected by flow conditions (BIO-WEST, 2014b). It is still unclear what ecological or behavioral conclusions about CSRB can be drawn from experiments using surrogates, which have been used in other 2014 Applied Research projects (e.g., plastron studies).

TABLE 5-3 Comal Springs Riffle Beetle Applied Research Projects

Study Title	**Year**	**Objective**
1. Extended Low-Flow Period Effects on Comal Springs Riffle Beetles	2014	To study CSRB survivorship inside of the springs during periods of low flow and flow cessation, including associated physical (i.e. temperature) and chemical (i.e. DO, pH, conductivity) changes. They designed "aquaria" that allow replicate samples and manipulation of flows to simulate up-welling, middle-welling and top-welling. Final report completed (BIO-WEST, 2014b).
2. Determination of Limitations of Comal Springs Riffle Beetle Plastron Use During Low-Flow	2014	Adult riffle beetles have fine hairs (plastron) that trap air next to their body, acting as a gill to breath underwater. Plastrons require clean, cool water to function. Determination of the limitations of the plastron to reduced dissolved oxygen levels and elevated temperatures would be useful in habitat management and modeling for the conservation of the CSRB. Proposal available (Gibson et al., 2013).
3. Estimate Comal Springs Riffle Beetle Population in Comal Springs/Landa Lake	2014	Sample a random distribution of previously sampled and unsampled springs for CSRB within Comal Springs/Landa Lake to estimate the CSRB population. Proposal available (Zara Environmental, 2013) but project just started.
4. Comal Springs Riffle Beetle Habitat Connectivity	2015	Evaluate the importance of the surface, riparian and submerged food sources to the ecology of the CSRB at the springs. Proposal available (BIO-WEST Project Team, 2014c).

Study #2 proposed to better evaluate the limitations of plastron respiration of the CSRB to reduced dissolved oxygen levels and elevated temperatures for use in habitat management and modeling of the CSRB. This project shares the same potential limitations as the extended low-flow study above, since a surrogate beetle species is being used pending approval for using CSRB itself. Additionally, without understanding the life history (e.g., number of generations per year and timing of different life stages during any given month) of the CSRB, this information will have limited meaning for habitat management. It is also not clear from the proposal if only adults will be studied (much like the biomonitoring) or if both adults and immatures will be evaluated in these laboratory studies. There are important physiological differences between adult and immature beetles that are often species-specific. Further, this project represents an attempt to understand the mechanistic reasons for beetle death due to low oxygen or higher temperatures in controlled laboratory experiments without any understanding of the natural changes in population numbers related to the CSRB life cycle in its actual habitat. Filling the gaps in life history information would provide more relevant information to the HCP for future modeling and management.

Study #3 is a survey of the distribution of CSRB in previously sampled and unsampled springs within the Comal Springs/Landa Lake system, meant to provide important data for estimating the CSRB population. This is a critical study for providing relevant and needed information about CSRB for the future ecological modeling efforts. Although it does not include sampling to provide life history information, the project will test the sampling methodologies and

detectability of the CSRB, in addition to identifying potential new habitats where there are populations of this threatened species. This project, which was on hold pending approval to amend the scientific permit for take and only recently began, should continue to be given high priority.

The goal of the 2015 proposed field study (Study #4) is to evaluate the importance of the surface, riparian, and submerged food sources to the ecology of the CSRB at the springs. Any field study that determines how current CSRB populations are potentially connected via habitat conduits could be important for habitat modeling and management decisions. Coupled with a better understanding of the life history features and habitat distribution of the CSRB (see Chapter 3), the results from this project could be quite informative to future modeling and management of this species.

NEW STUDIES THAT SHOULD BE PART OF THE APPLIED RESEAERCH PROGRAM

Fountain Darter

Several areas should be considered for future applied research on fountain darter. First, additional studies on movement would be beneficial, preferably allowing for Lagrangian tracks to be estimated. Various types of mark-recapture and tracking technologies should be investigated and tested to determine movement ranges and patterns under a range of environmental (e.g., spring flow) conditions. Sampling should involve different sizes of fountain darter during each of the key seasons. Understanding the movement patterns of individuals will provide information on the movement exchanges among habitat areas, range size, and provide data for model calibration and validation.

A second set of special studies could confront the persistent lack of a relationship found between flow and fountain darter metrics. While we expect such a relationship at the very extremes of low flows, it is critical to refine the relationship at low to moderate flows and also at high flows (scour events). Changing flows can have effects on growth, mortality, and reproduction that can affect multiple life stages and accumulate over time, resulting in important effects at the population level. These relationships need to be delineated based on empirical evidence and, in some cases, quantified. While the planned flow-triggered sampling is a good idea, these measurements could be further supported by studies that use lab and field measurements to ensure responses are recorded over a range of flows. This is challenging because fish integrate the environmental conditions they experience, and measurements of flow are instantaneous.

A third issue is obtaining measurements related to individual fountain darter health that go beyond the densities and lengths of individuals measured in the current biomonitoring. Densities have high variability and are difficult to extrapolate spatially, and lengths alone are a relatively insensitive indicator of fish responses to conditions. There have been many bioindicators proposed that reflect the health of individual fish (Adams, 1990; Adams and Ham, 2011; Kim et al., 2012; Hasler et al., 2009), including variations on the classic condition index (Courtney and Courtney, 2014), non-lethal estimation of tissue composition (Cox and Hartmann,

2005), and determination of the number of samples needed (Gagnon and Hodson, 2012). There may be logistical issues in terms of not being allowed to sacrifice the darters to obtain the measurements, but this is worth exploring as a special study.

The use of habitat area, darter densities, and flow criteria to assess the health of the fountain darter population relies on mostly correlative evidence, and thus has a certain level of uncertainty when used to predict responses to changing flow conditions. While there is great value in this approach, it could be strengthened substantially over time with the addition of active research to determine more mechanistically how individual darters and habitat types interact to affect the former's growth, mortality, reproduction, and movement.

For all of the Applied Research studies that are designed to support the modeling, a clear description of how the results will inform the modeling should be required. Results should inform how growth, reproduction, mortality, or movement is represented in the model, or they should be used for model-data comparisons (calibration or validation). As the ecological modeling for fountain darter proceeds, close interaction between model development and periodic sensitivity and uncertainty analysis should be used to help identify critical unknowns and assumptions that would benefit from additional experimental and field data collection.

Submersed Aquatic Vegetation and Texas Wild Rice

The Applied Research projects for SAV should address the needs of the SAV modeling efforts by focusing on supplying data on SAV growth, dispersal, and recolonization for those SAV species that are the best habitat for the fountain darter. New studies that elucidate the interactions between SAV and the fountain darter would be particularly helpful, for example, determining once and for all which SAV species provide the best habitat and why. Are the fish using SAV for protection, to find food, and/or as a nursery area for young? Why do fountain darters prefer bryophytes and filamentous algae, which are not vascular plants, and how can that be incorporated into the SAV model?

For Texas wild rice, studies should focus on the restoration of this plant, in particular in areas that are considered suitable habitat yet are devoid of this plant (as discussed at length in the Chapter 3 recommendations). Applied research studies could examine many aspects of Texas wild rice restoration, including planting Texas wild rice in suitable areas and monitoring for success, determining the effects of restricting recreation from areas where Texas wild rice is growing under various flow rates, and determining whether low flow conditions are more detrimental to Texas wild rice than recreation.

Comal Springs Riffle Beetle

As discussed in Chapters 3 and 4, life history, life cycle, and spatial distribution information for CSRB is necessary for better modeling of this species. The main information gap is the lack of life history information on the CSRB, including information on true densities of both immature and adult life stages throughout the year, growth rates of the life stages, how many generations occur each year and are they synchronous, how fast the life cycle proceeds, or how the life cycle and other life history attributes like fecundity might be affected by changing

flow or sediment conditions. Such information provides the foundation for developing a life table (stage-specific durations, mortality rates, and reproduction) and eventually a population dynamics model. While generating such information is formidable in the short-term, striving to obtain information that would eventually allow development of a population model for CSRB is a necessary long-term goal.

From the data presented in the biomonitoring reports it is not clear if the adults and immature stages always share the same habitat in both space and time. This is a critical piece of information because the long-term population trends (BIO-WEST, 2014c) that have been reported have only reported adult numbers. In order to acquire this information, it will be important for the HCP to identify how representative the currently sampling method (i.e., cotton lures) is to quantitative densities of both adult and immature stages of the CSRB.

One of the Applied Research studies for 2014 begins to address some of this information, namely Study #3, *Estimate Comal Springs Riffle Beetle Population in Comal Springs/Landa Lake*. However, this project does not identify life history information important to better understanding how the populations, or portions of them, respond to changing habitat conditions related to flow or sedimentation.

Finally, as discussed in Chapter 4, a better assessment of how well the CSRB acts as an indicator species for the other listed species will be critical for more comprehensive management of all threatened or endangered species that are not currently being monitored.

Phosphorus Sources, Cycling, and Availability

The annual summer green algal blooms in the Upper Spring Run reach of the Comal River indicate that there is an abundance of nutrients in the Comal system. These could be from natural sources or of anthropogenic origin. Anecdotal evidence presented in the algal decay proposal (BIO-WEST Project Team, 2104a) suggests that the blooms tend to accompany low flow and high temperature conditions. This indicates a strong likelihood that nutrients, particularly phosphorus, are coming from an internal source, such as sediments.

Many, if not most, productive aquatic systems are characterized as having relatively high nutrient levels in the bottom sediments, which have built up over decades of sedimentation and decomposition of organic matter. These bottom sediments, serving generally as nutrient sinks, also can be important sources of nutrients at certain times. In productive stratified (thermally and chemically) lakes, the sediments and hypolimnetic (bottom) waters are usually devoid of oxygen and are thus conducive to redox-dependent dissolution of inorganic phosphorus complexes, which upon destratification (e.g., fall overturn) can return to the surface waters as a major source of available phosphorus. In productive shallow systems, stratification is less stable, often occurs on a diurnal basis, and involves the chemical stratification at the sediment-water interface. In such cases, anoxia and redox-dependent dissolution of inorganic phosphorus complexes can occur each night, as respiration dominates biological activity. Each morning, when the chemical stratification breaks down, the newly released phosphorus is available to the biota (i.e., algae) in the water column. Such a system has been described as a phosphorus pump (Hambright and Eckert, 2001) and can lead to relatively high levels of sedimentary phosphorus release in productive systems.

It could prove highly beneficial to the HCP to have a better understanding of the nutrient budgets in the two spring systems, particularly since flow and the potential impact of internal nutrient loading will likely be inversely related. In other words, in addition to the physical impacts of low flow, there could be very important indirect effects of low flow on the overall productivity and food web dynamics of the spring/river ecosystems due to nutrients.

A call for proposals to investigate and document P (and N) dynamics could attract scientists from across the country.

WORKING TOWARD AN ECOSYSTEM FRAMEWORK

The Applied Research projects for 2013 and 2014, as well as those planned for 2015, are generally useful for filling knowledge gaps and improving the planned ecological modeling efforts. However, the current program is directed toward individual species rather than the ecosystem as a whole. As discussed in Chapter 3, a generalized conceptual model of the entire Comal and San Marcos Springs ecosystems would provide a much needed foundation for guiding the Applied Research Program. Whether a single broad-scale model or a series of models at issue-specific scales, a framework encompassing all covered species, their potential interactions and drivers, and all available management actions, would empower the EAA with a common language accessible to stakeholders, scientists, and the general public. Such a framework would also allow efficient prioritization of projects. For example, the primary driver of the Incidental Take Permit and the HCP is spring flow, and yet there is still no clear picture of how spring flow will impact either the indicator species or the covered species as a whole. Indeed, only one of the indicator species, fountain darter, is designated for modeling, while there are no apparent plans for developing models for Texas wild rice and CSRB. It is expected that the relationships between spring flow and population sizes of fountain darter, CSRB, and Texas wild rice, as well as other covered species, will be highly nonlinear and complex, with multiple indirect forcing factors.

ENHANCING REVIEW AND OVERSIGHT IN THE APPLIED RESEARCH PROGRAM

The Applied Research Program is the EAA's main tool to fill a broad range of knowledge gaps necessary for the successful implementation of the HCP. The scientists and engineers that currently conduct much of this research are knowledgeable and experienced in the system and they represent the disciplines necessary to support work on species ecology, but they may not fully recognize their limitations or needs outside their area of expertise. The program would benefit by ensuring review, evaluation, and oversight from a broad range of stakeholders and by soliciting researchers from a broader range of disciplines as needs arise. Means of achieving this would be (1) more effective use of an advisory committee, such as the Science Committee, and (2) more open solicitations for projects. The membership of the advisory committee should be reviewed to ensure adequate representation from the stakeholder communities as well as the scientific disciplines necessary to address all aspects of the HCP. The use of this advisory committee early in the process to identify research needs and help write the project solicitations would encourage stakeholder input and ensure that all knowledge gaps limiting achievement of

HCP goals could be identified and addressed. Use of currently funded investigators to define critical research areas is good practice, but their suggestions should go to the advisory committee for evaluation of the quality and merit of the research based on their own expertise as well as on reviews from outside researchers/scientists who are not associated with the HCP. That is, there should be a clear and procedural separation between the suggestions of the currently funded investigators and the selection of topics to be targeted in solicitations.

The use of an open solicitation that is widely distributed to universities, other research organizations, and the consulting community could help ensure that the expertise required to conduct the research is also available. The advisory committee, likely the current or expanded Science Committee, should again be engaged to help review and evaluate responses to the solicitation and provide input to the selection of the research projects. In addition to helping ensure that the best projects are identified and conducted, greater stakeholder involvement and engagement through the advisory committee would help ensure greater acceptance of the outcomes.

External peer review should also be employed to strengthen the quality and completeness of the Applied Research Program, particularly for proposals in disciplinary areas not well represented by the current Science Committee. Use of peer review is a critical aspect of developing a science-based HCP that is accepted by the various agencies and stakeholder groups.

A key aspect of fully utilizing peer review is a documentation trail of a request for proposals, material presented to the committee, outside reviewer comments, the committee evaluations, responses to the committee evaluations, and final committee recommendations. This documentation is critical to ensure the benefits of peer review and to ensure a transparent process for stakeholders and the general public. To aid transparency, a standard process should be adopted and followed for peer review of all project proposals including when peer review will be limited to the Science Committee versus external reviewers.

The HCP states that biological goals and objectives formulated are based on the best "scientific and commercial data available." This statement appears to indicate that "scientific" data are from the published peer-reviewed literature, while "commercial data" are from non-peer-reviewed reports prepared within the consulting industry. Obviously, both types of data could be of equal quality and value, and management and protection of endangered species probably should not always wait for the peer-review system to run its course. However, peer-review, whether conducted by the Science Committee or external reviewers, offers the best approach for identifying sound, evidence-based research on which the HCP should be based.

RECOMMENDATIONS FOR THE APPLIED RESEARCH PROGRAM

Through long-established collaborative partnerships with BIO-WEST, Zara, Texas State University, U.S. Fish and Wildlife Service, and other researchers, the EAA has a sound foundation for development of a proactive research program that will provide the needed scientific understanding to ensure a successful HCP. The Committee recommends that the EAA consider the following structural modifications to further increase the usefulness and efficiency of the current research program.

Project partners should be tasked with the development of a general conceptual model for the Comal and San Marcos ecosystems. As discussed in Chapter 3, these models should include all covered species, their potential interactions and drivers, and all available management actions, and will serve as important road maps for all future developments within the HCP.

The Applied Research Program would benefit from a more transparent process for prioritizing and funding projects that includes stakeholder involvement, for example through the Science Committee, and peer review.

The Applied Research Program would benefit from greater competition and collaboration with outside scientific experts through open and widely disseminated solicitations for research. Increasing the diversity of thought, understanding, and perspective will serve to strengthen the HCP and increase the likelihood that project goals will be met.

The program should offer some longer-term (e.g., two- to five-year) projects in order to maximize interest and collaboration from the region's leading researchers. Multiple-year project proposals could be awarded with the simple limitation that funding in subsequent years is contingent on funding availability, project needs, and project success.

Results from the Applied Research Program, particularly from outside researchers, should be provided in a form that ensures transparency and accessibility to other researchers and to the EAA. One means of doing this is a standard data management structure to which all research projects must adhere.

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6

Overarching Issues

The Edwards Aquifer Authority (EAA) and other Permittees are at the beginning stages of implementing a complex Habitat Conservation Plan (HCP) and are doing an excellent job in many respects, such as fountain darter biomonitoring. Nevertheless, in the course of reviewing the EAA's modeling and monitoring efforts for this report, the Committee has identified a number of overarching concerns regarding the implementation process—concerns that may hinder the later stages of this HCP and especially any future attempts to renew the HCP and the Edwards Aquifer Incidental Take Permit. This chapter presents these overarching concerns and offers suggestions for broader-based improvements to the HCP's implementation. These suggestions all underscore a recommendation that the EAA and other Permittees begin thinking now about how best to manage the very long-term process of protecting the ESA-listed species, from data management and analysis to scenario planning.

BENEFITS OF INTEGRATION

The present suite of data collection activities and analyses found in the HCP combines monitoring, modeling, and various individual experiments and field studies into a larger overall science program. This multifaceted approach has advantages in being flexible and efficient because the various small pieces can be modified and staffed by relatively few people and new pieces can be added relatively quickly. However, without careful attention to integration and coordination across the entire project, inconsistencies in methods and analyses among the individual studies can occur, key elements of study can be omitted, and observational data may not be collected in a manner that best informs model development and evaluation. Because the EAA contracts with outside groups to conduct much of the research and monitoring and each of the contractors may not be fully aware of all program elements, it is particularly important that the EAA place special emphasis on careful integration of the overall program. Increased effort to integrate and synthesize data and research would enable the clear explanation of a cohesive set of results and conclusions that would increase the transparency and credibility of the science underlying the HCP.

Without clear attention to project integration, there is danger that the EAA efforts might result in a number of separate projects that do not combine seamlessly into an overall science program. For example, the water quality and biological monitoring programs developed somewhat independently and are not well integrated with each other (see Chapter 4), nor are they integrated with the hydrologic monitoring done outside the HCP (see Box 2-3). Sampling sites are not co-located to the extent that they could be. In addition, biological monitoring is largely focused on the various species of interest and could benefit from a broader focus on the

biological communities in which these species are embedded and the multiple drivers that can influence these biological communities. Developing explicit linkages between hydrogeological, surface water, and biological processes would be of significant benefit to the long term goals of the HCP.

There also appears to be a lack of integration between the hydrogeologic modeling and research efforts. The hydrogeologic science investigations are conducted largely separately from the HCP and are not included in the Applied Research Program. While the hydrologic science program (Box 2-3) provides critical information for modeling and ecosystem assessment, the lack of a formal commitment means that research priorities may not be directed toward key questions in the HCP, especially if budgets become limited. For example, while there are plans to investigate the connection between the Comal and San Marcos pools under different hydrologic stresses, the priority of this research in the hydrogeologic science program is not clear. Nor is there a direct opportunity for groundwater modeling studies to inform the research plans. For example, as pointed out in the modeling sections of Chapter 2, specific tracer tests done by the hydrologic science program might benefit the conceptual model of the aquifer. Effects of climate change could be investigated by looking at long-term hydrologic data trends and incorporating them into the models, which would be helpful in developing adaptive management plans. Lack of coordination between the research efforts and the modeling team could delay improvements to the hydrologic modeling efforts. That being said, it is hoped that more formal coordination of the hydrogeologic research with the modeling efforts in the HCP could be implemented without adding layers of review that might slow the research process.

The Committee has identified several steps that can be taken to enhance integration of the HCP program.

1. Develop an overall conceptual model of the system, including hydrological, climate, and biological community components. Such a model can guide the development of quantitative modeling of sub-components, identify gaps in understanding, and provide context for understanding the responses of particular species of interest. This overall conceptual model (or models) should be integrated with and cross-referenced to the more focused conceptual models on key species population dynamics. Such a set of conceptual models would be particularly valuable to understanding the multiple drivers of fountain darter population dynamics, including spring flow, climate variability, land use change, water quality, predation, and habitat.

2. Develop a unified data/information management system so data are easily available to all project teams. This recommendation is described in the next section of this chapter.

3. Convene an annual science meeting to discuss results, discover gaps in understanding, and help plan future studies and monitoring activities. Such a meeting should include all project and contract scientists, other university and agency scientists who might be interested in becoming involved in future studies, and various stakeholder groups. These meetings can provide excellent forums to discuss results to date and provide transparency in identifying future research, monitoring, and modeling needs. The ability of the Science Committee to effectively engage and advise the Applied Research and other programs could be enhanced through this process.

DATA AND INFORMATION MANAGEMENT

The HCP is data-intensive, including hydrological, meteorological, chemical, and biological data collected at a variety of spatial and temporal frequencies and extents. Users and providers of HCP-relevant data include a diverse set of individuals and groups from academia, non-governmental organizations, commercial institutions, and municipal, state and federal agencies. Rich sets of legacy data on multiple aspects of the Edwards Aquifer have been collected by numerous groups prior to the adoption of the HCP. Ongoing data collection as part of specific short-term studies or long-term monitoring is planned or underway as part of the HCP. The hydrological and ecological modeling that forms a core part of the HCP will produce large amounts of model output. Finally, all of these efforts will be repeated in 15 years when the Incidental Take Permit (ITP) needs to be renewed. The data emanating from these various activities need to be organized, quality assured, maintained, and curated. Furthermore, the data must be accessible, discoverable, reviewable, and useable by individuals or groups both within and outside of the HCP set of stakeholders.

The Committee strongly recommends that the EAA develop a comprehensive information management plan as soon as possible. Such a plan would ensure both internal and external access to relevant data over both the short- and long-term, facilitate data analyses and syntheses across multiple data types and sources, buffer against the potential turnover of key personnel, and increase transparency and communication across stakeholders as the HCP is implemented and evaluated. In short, a well-planned and implemented information management system will make all aspects of the HCP more likely to succeed. The need for high quality data organization is evident when reviewing the multiple reports that can include data collected using different methodologies and approaches. There appears to be no attempt to collate these data sets in a way to provide rigorous statistical evaluation of long-term trends or interactions among ecological components. Further, there appears to be no clearly defined standard operating protocol for data sharing and management. The plan should include multiple aspects of information management such as:

- definition of data types and formats ranging from raw data to metadata; what types of data are available and how are they characterized and organized;
- explicit data management plan, from the method of collecting and initially transferring data from the field into digital form, to follow-up data flow consisting of (but not limited to) quality control, analysis, synthesis and dissemination;
- agreements about which data, and types, will be centrally housed and which will be distributed among individual stakeholders;
- maintenance of database integrity including quality assurance and short- and long-term curation, archival and data back-up plans;
- description of the data access and sharing policy;
- creation of an accessible environment for the retrieval of information;
- facilitation of linkages among diverse data sets;
- documentation of metadata for data interpretation and analysis; and
- analysis of information management staffing needs.

Developing and implementing a comprehensive plan is not trivial, and adequate time and resources should be made available. Full-time staffing by trained information managers will likely be required throughout the life of the project. Other complex, data-intensive projects such

as the Long-Term Ecological Research Network, the Consortium of Universities for the Advancement of Hydrological Sciences, Inc., and the Ecological Society of America have developed functional information management and data registry systems that might serve as models for the EAA.

PERFORMANCE MONITORING OF MINIMIZATION/MITIGATION MEASURES

The HCP includes multiple minimization and mitigation (M&M) measures related to habitat and vegetation restoration, including reduction of recreational impacts, removal of exotic species, bank stabilization, and planting of Texas wild rice. It is unclear how the EAA is quantifying either the M&M measures themselves or the responses of the various target species, making it difficult to determine whether the measures are effective. **The Committee recommends that the M&M measures be monitored for their performance.** They should also be explicitly integrated into the ecological modeling and Applied Research efforts, preferably in the form of experimental analyses with the intent of testing and ultimately improving the ecological models.

NEED FOR ADDITIONAL DATA ANALYSIS

The Committee has observed that much of the data found in documents supporting the HCP do not include error bars or other measures that demonstrate the variability of the data or the uncertainty of model predictions. More formal statistical analysis, such as the incorporation of variance into estimated means and other summary statistics, would give additional credibility to the scientific basis of the HCP process. There is significant opportunity for exploring the key field datasets and model results, both ecological and hydrological, with more advanced statistical methods than simple summary statistics and graphical plotting. Some of the recent final reports from the Applied Research Program used standard statistical methods as part of their analyses, and this should be the continued expectation for all HCP research. **The Committee recommends that the EAA undertake more formal and rigorous statistical analyses of its laboratory and field data.**

Such statistical (exploratory) analyses do not replace the summary statistics and plotting analyses being done now, which are appropriate, but rather act as complementary analyses. Examples of where statistical methods should be applied with the ecological monitoring data are the derivation of the habitat suitability functions and power analyses of future trend evaluations. To date, habitat suitability functions have been drawn by hand using expert opinion and the available field data. A statistical definition of current conditions and the collection of data appropriate to define statistically significant future trends are critical to the evaluation of those trends. With the accumulation of more field data and laboratory results, a more statistically based fitting of the habitat suitability functions should be conducted. Modeling of habitat utilization has become a very active area of research (Guisan and Zimmermann, 2000; Guisan and Thuiller, 2005; Feyrer et al., 2011; Knudby et al., 2010), partly because of interest in predicting the responses to climate change and partly because of the development of robust statistical methods. Statistically based habitat suitability functions would then be compared to

expert opinion functions to assess similarities and differences, and both could be used in analyses to bound predictions of habitat changes in response to spring flows.

The biomonitoring field data will be increasingly used for examining temporal trends in the indicator species and their correlation to environmental variables such as flow. This will be especially true for the fountain darter in the index reaches. The issue of how to interpret the biological significance of sudden drops in the density of the indicator species will arise, and can be addressed by exploring trend detection methods and power analyses with the presently available data. These analyses will provide information on the likelihood that different magnitude and duration changes in the indicator species densities are significant relative to past variation. The exact methods to use depend on the specific statistical methods selected for the trend and correlation analyses and also on the preliminary results of those analyses. However, the general philosophy of power analyses (whereby the data are simulated with different types of variance and then sampled and analyzed with the trend and correlation methods) is well accepted and can be implemented in most statistical software packages (e.g., R statistical programming language). There are also exploratory data analysis methods that should be investigated to identify less-than-obvious patterns in spatial time series data, such as indicator densities and flows measured at multiple locations. These methods and analyses should be explored to help focus further field and lab data collection that would further elucidate flow-fish relationships.

The application of statistical methods in hydrological analysis is primarily associated with quantitative uncertainty analysis of model predictions, discussed in detail in Chapter 2.

POSSIBLE SCENARIOS OF FUTURE CONCERN AND SCENARIO PLANNING

One notable aspect of the current implementation of the HCP is a prevailing assumption that relevant conditions—both legal and ecological—will remain relatively stable throughout the Plan’s 15-year implementation period and that the worst case drought conditions were those observed during the drought of record in the mid-1950s. For example, EAA representatives indicated that they plan to consider climate change and its predicted impacts on the Aquifer (and on demands for Aquifer water) only in the next phase of implementation.

The Committee recommends that the entities implementing the HCP begin to think now about possible worst case scenarios and their potential implications for both modeling and HCP implementation. On the modeling side, the Permittees should consider whether the models currently being developed rest on ecological assumptions that could be altered by a changing climate and, if so, whether potential or predicted alterations can themselves be incorporated into the model. Another modeling issue may be whether the models being developed can alert the Permittees to potential discontinuities and ecological thresholds in the Edwards Aquifer system under different future climate scenarios.

On the implementation side, considering potential future changes now could allow the Permittees to develop contingency plans—ecological, political, or legal—for future “worst case” scenarios, building adaptability, flexibility, and resilience into the HCP’s execution. Scenario building is a widely recognized and approved strategy for adaptation planning (Hannah et al., 2002; Shaw et al., 2009) that a number of resource agencies are employing throughout the United States (e.g., NPS, 2013). Moreover, scenario building could also help the Permittees to identify in advance situations that might require amendments to the HCP itself or to the legal

authorities of the various Permittees. The Committee suggests that at least six potential future "worst case" scenarios are worth considering. It will be important for the Permittees to have the expertise (e.g., risk assessment, social sciences) needed to address these scenarios.

Scenario #1: Increased Groundwater Pumping from Exempt/Unregulated Wells Undermines the HCP's Minimum Flow Requirements

Under the Edwards Aquifer Authority Act, wells that produce less than 25,000 gallons per day of water are exempt from many of the Act's requirements (EAAA § 1.33; EAA Rules §§ 702.1(70), 711.14, 711.20). There has been anecdotal evidence during the drought of 2014 that a number of landowners are drilling exempt wells within the Edwards Aquifer region (although the EAA has not provided the Committee with the cumulative number of exempt wells). If landowners are increasingly using this legal exemption, their cumulative pumping could undermine the HCP's minimum flow requirements, especially during drought years, regardless of how well the Permittees implement the HCP's measures. As a result, the Permittees may have to ask the Texas Legislature to retroactively close this loophole in the Edwards Aquifer Authority Act.

Scenario #2: Drought Conditions Exceed the Drought of Record

The entirety of the HCP is built on the premise that the drought of record will be the worst that drought ever gets for the Edwards Aquifer region. What if that premise is wrong? What happens, for example, if the Edwards Aquifer region experiences a worse drought than the drought of record that lasts for several more years? What happens if the Edwards Aquifer region experiences several droughts of record (or even near droughts of record) in succession? The current drought in Texas began in 2011 and persists across much of the state, including the San Antonio region where Stage 3 Critical Period Management is in effect.

It should be noted that tree ring analyses suggest that decadal-scale droughts, including mega-droughts of 15 to 30 years duration, have occurred in Texas at least once every 100 years since the 1500s (Cleaveland et al., 2011). Moreover, the external review (EARIP, 2012, Appendix I) of the Hardy (2009) report felt that "the presumption that a drought will mirror a previous one in climatic intensity or with the same combination of factors [water quality parameters same as in 1950s, watershed conditions similar (e.g., impervious cover), connectivity constraints similar, biotic interactions similar (e.g., invasive species threats the same), demand for water and recreational demand the same, etc.], does not seem probable." Thus, the 1950s drought likely does not represent the true worst-case scenario as a baseline for hydrological modeling.

Scenario #3: Mismatch between Conservation Triggers and Hydrologic Changes

Many of the triggering events for the HCP's water conservation measures are tied to hydrologic conditions on a particular date each year. Have the HCP Permittees considered the risks to the system, to the ESA-listed species, and to implementation of the Plan itself from a

"perfect storm" of bad timing of these key events? For example, what happens if low-flow conditions occur immediately after the October triggering date for water conservation measures and last well into the next year?

Scenario #4: Climate Change Impacts Become Significant Faster Than Expected

The impacts of climate change are already being felt in many parts of the country, and one of the most important lessons for both modeling and planning is to *not* assume stationarity in baseline ecological conditions such as precipitation, evapotranspiration, and hydrologic flow. Have the HCP Permittees developed monitoring plans that will alert them to changing or potentially changing baseline conditions, models that incorporate changing baseline conditions, and contingency plans that will allow the HCP to remain viable if climate change impacts become significant within the period of the ITP?

Scenario #5: High Court Affirmation of the *Bragg* Constitutional Takings Decision

Bragg, as noted in Chapter 1, found that limiting the overlying landowners' ability to pump water from the Edwards Aquifer could result in a constitutional taking of their property rights, requiring payment from the EAA. This decision could potentially undermine the economic and legal assumptions of the HCP, and the Permittees should consider the following issues:

a. If *Bragg* is upheld on appeal, to how many groundwater permits is it likely to apply?
b. If *Bragg* is upheld on appeal, will the EAA still be able, financially, to implement the HCP and the Act's restrictions on groundwater pumping in the Edwards Aquifer?
c. If *Bragg* is upheld on appeal and its implications undermine the EAA's ability to implement the HCP, how do the Permittees plan to move forward? Will they abandon the HCP entirely, understanding that ESA Section 9 "take" liability may arise as a result? Do they expect the Texas Legislature to intervene in support of the HCP, either financially or legally? Might management of the Edwards Aquifer at that point be turned over to the relevant federal agencies, as the original 1993 federal court decision threatened? In short, do the HCP Permittees have a contingency plan in place to deal with *Bragg* if that decision is upheld and its application undermines implementation of the current HCP?

Scenario #6: Subjugation to Aransas National Wildlife Refuge ESA Issues

The Edwards Aquifer is directly connected to the Guadalupe and San Antonio Rivers, which in turn flow to San Antonio Bay and the Aransas National Wildlife Refuge, which in turn provides habitat to the ESA-listed whooping crane. According to the HCP, the whooping crane was not included for coverage in the Edwards Aquifer HCP because it is believed that: (1) factors affecting the crane and its habitat are not under the control of the EAA and partner

Applicants for the ITP; and (2) that whooping cranes would not be affected adversely by the Covered Activities. In addition, the HCP states that the minimization and mitigation measures developed for the activities covered by the proposed permit should provide greater stability in the flows emerging from the spring systems at Comal and San Marcos Springs and, therefore, are expected to provide a potential net benefit to the habitat conditions for the ecosystem used by the crane.

Nevertheless, in March 2013, in *The Aransas Project v. Shaw*, 930 F. Supp. 2d 716, 786-88 (S.D. Tex. 2013), the U.S. District Court for the Southern District of Texas concluded that the Texas Commission on Environmental Quality had effectuated a Section 9 "take" of ESA-listed whooping cranes as a result of state-permitted diversions of fresh water. While the U.S. Court of Appeals for the Fifth Circuit reversed the liability finding on proximate causation grounds in June 2014 [*The Aransas Project v. Shaw*, 756 F.3d 801, 816-23 (5th Cir. 2014)], the case nevertheless still made clear that water flows in the larger watershed are important to the continued survival of the cranes. Moreover, the plaintiffs in that case considered whether they should include the EAA and other upstream water users in the litigation. Although the plaintiffs ultimately decided *not* to seek defendants so far upstream, the decision nevertheless suggests that the Edwards Aquifer could become tied to a much larger ESA recovery process and plan like the one that has enveloped the Snake River in Idaho (NOAA Fisheries, 2014). Have the HCP Permittees considered the implications for the Edwards Aquifer if it becomes linked to the Aransas National Wildlife Refuge in ESA recovery planning? What might that mean for Edwards Aquifer management and the necessary modeling for the system? How might such a linkage affect the water conservation requirements and pumping limitations imposed on the Edwards Aquifer? Would the needs of the whooping cranes in effect drive most or all of the management of the Edwards Aquifer?

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Acronyms

ASR	aquifer storage and recovery
BMP	best management practice
CFS	cubic feet per second
CSRB	Comal Springs riffle beetle
CTM	critical thermal maximum
DFN	discrete fracture network
DO	dissolved oxygen
EAA	Edwards Aquifer Authority
EAHCP	Edwards Aquifer Habitat Conservation Plan
EARIP	Edwards Aquifer Recovery Implementation Program
EPM	equivalent porous medium
ERPA	Environmental Restoration and Protection Area
ESA	Endangered Species Act
FE	finite element
FWS	U.S. Fish and Wildlife Service
GMRP	Groundwater Model Review Panel
GPS	global positioning system
GSI	gonadosomatic index
HCP	Habitat Conservation Plan
HSPF	Hydrological Simulation Program—Fortran
IBM	individual-based model
ITP	Incidental Take Permit
LID	Low Impact Development
M&M	minimization and mitigation
NRC	National Research Council
PCBs	polychlorinated biphenyls
RMS	root mean square
SAV	submersed aquatic vegetation
SAWS	San Antonio Water System
SVOCs	semivolatile organic compounds
SWRI	Southwest Research Institute
TDS	total dissolved solids
TOC	total organic carbon
TPWD	Texas Parks and Wildlife Department
TWR	Texas wild rice
USGS	U.S. Geological Survey

VOCs	volatile organic compounds
VISPO	voluntary irrigation suspension program
WUA	weighted usable area

Appendix O2

Study Announcement
Review of the Edwards Aquifer Habitat Conservation Program – Phase 2

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

Water Science and Technology Board
Division on Earth and Life Studies

September 2015

Study Announcement

Review of the Edwards Aquifer Habitat Conservation Program—Phase 2

A committee of the National Research Council (NRC) continues to review the different scientific initiatives underway to support the Edwards Aquifer Habitat Conservation Plan (HCP). The Edwards Aquifer provides drinking water for over two million people in south central Texas and it supports many agricultural, industrial, and recreational uses. It also provides habitat for eight federally protected species of fish, invertebrates, amphibians, and Texas wild rice.

The committee is focusing 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. It will evaluate the relationships among proposed conservation measures (like flow protection and habitat restoration), biological objectives (like specified flow rates), and biological goals (like maintaining populations of the covered species). In early 2015 the committee issued its first report, which focused on hydrologic modeling, ecological modeling, water quality and biomonitoring, and the Applied Research Program. In its second report, due in late 2016, the Committee will:

1. evaluate progress and modifications implemented as a result of its first report,
2. continue to assess the methods of and data collected through the water quality monitoring and biomonitoring programs,
3. identify those biological and hydrological questions related to achieving compliance with the HCP's biological goals and objectives that the ecological and hydrologic models should be used to answer, specifically including which scenarios to run in the models. These questions shall help generate information needed to make the HCP Phase II strategic decisions about the effectiveness of conservation measures.
4. provide an evaluation of how the Phase I conservation measures in the HCP (including flow protection measures and habitat restoration measures) are being implemented and monitored. Specifically, the committee will discuss if the proper method of implementation is being utilized to achieve the maximum benefit to the covered species.

The committee is chaired by Danny D. Reible, Texas Tech University, and a member of the National Academy of Engineering. Dr. Laura Ehlers of the NRC's Water Science and Technology Board serves as the study director (lehlers@nas.edu). The committee members are:

Danny D. Reible, *Chair*, Texas Tech University, Lubbock
Jonathan D. Arthur, Florida Geological Survey, Tallahassee
M. Eric Benbow, Michigan State University, East Lansing
Robin K. Craig, University of Utah, Salt Lake City
K. David Hambright, University of Oklahoma, Norman
Lora Harris, University of Maryland, Horn Point
Timothy K. Kratz, University of Wisconsin, Madison
Andrew J. Long, USGS, Tacoma, Washington
Jayantha Obeysekera, South Florida Water Management District, West Palm Beach
Kenneth A. Rose, Louisiana State University, Baton Rouge
Laura Toran, Temple University, Philadelphia, PA
Greg D. Woodside, Orange County Water District, Fountain Valley, CA