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Final Report (Revised)
Cooperative Agreement #xxxx-xxxxxx-xx-xxxx
May 30, 1999
Acknowledgments

This research was funded by: (1) the U.S. Fish and Wildlife Service, Ecological Services Field Office, Austin, Texas; (2) The Vice President of Research, Utah State University; (3) Utah Water Research Laboratory, Utah State University; and (4) Institute for Natural Systems University, Utah State University. This study would not have been possible without the support of the following people at the U.S. Fish and Wildlife Service: Paula Spears, Alisa Shull, Stephen Helfert, Bill Seawell, Thomas Brandt, Casey Berkhouse, and Joe Fries. Additional help was provided by Steve Cullinan, Jim Reed, and Louis DuBois.

Extensive collaborative help for field and laboratory studies were provided by dedicated personnel (past and present) from:

U.S. Fish and Wildlife Service -
Ecological Services Field Offices: Austin; Arlington, TX; Albuquerque; Corpus Christi; Houston; Phoenix, Green Bay; Charleston, SC; Concord, NH; and Barrington, IL
San Marcos National Fish Hatchery and Technology Center, San Marco, TX
Balcones Canyonlands National Wildlife Refuge, Austin

Utah State University, Institute for Natural Systems Engineering, Logan

Texas Parks and Wildlife Department
River Studies, San Marcos and A.E. Wood Fish Hatchery, San Marcos

San Marcos River Foundation

U.S. Geological Survey - Austin and San Antonio

We appreciate the extensive mapping efforts on the San Marcos River aquatic plant community by Dr. Robert Doyle and Matthew Francis of the University of North Texas and to Dr. Michael Smart, David Honnell and the U.S. Army Corps of Engineers’ Lewisville Aquatic Ecosystems Research Facility.

We wish to note significant contributions made by Karim Aziz, Kevin Mayes and others at Texas Parks and Wildlife Department. Their surveying data, including the edge of water and reference mark elevations greatly facilitated our study.

We sincerely thank the following landowners for allowing access to the river through their property: Ernest, Sally, and Alan Cummings; Kathryn and Bill Rich; Jim Smith; Glen Krause of the Smith Ranch for his invaluable help with GPS surveying and other field work; Jimmy Swaim of TPWD; A.E. Wood State Fish Hatchery for river access and temperature monitoring and water level gage placement; Robert and Russell Thornton for their significant help and support; the San Marcos Baptist Academy; Southwest Texas State University (Prof. Francis Rose and Ron Coley); and Chip Wood, formerly of San Marcos Parks and Recreation Department.
EXECUTIVE SUMMARY

This report details the results from a multi-year collaborative effort to quantify the physical, chemical and biological characteristics of the San Marcos River aquatic ecosystem and develop an applied assessment framework where these physical, chemical and biological elements can be integrated to assist decision makers in understanding the implications of alternative in-stream flow strategies for the protection, enhancement and recovery of endangered, threatened and sensitive species. The report focuses on the data collection methods and analyses utilized to characterize the physical, chemical and biological components as well as a description and application of the integrated assessment framework which links these elements for the evaluation of alternative spring discharge scenarios. This assessment framework also enabled the evaluation of the effects of partitioning flows to the mill race channel relative to flows to the main channel of the San Marcos River. For this report, the main species of focus were the fountain darter (*Etheostoma fonticola*), endemic only to the Comal and upper San Marcos river systems, and Texas wild-rice (*Zizania texana*), endemic only to the San Marcos River.

Seasonal field collections over several years were made throughout the San Marcos River utilizing a stratified, random sampling procedure, forming the basis of a physical, chemical and biological database. This database was used to statistically derive quantitative response functions to physical, chemical and biological variables for the darter. These functions were then used in the evaluation of flow dependant physical, chemical and biological properties within the San Marcos system using an integrated assessment framework. The assessment framework is composed of: (1) a spatially explicit 3-dimensional morphometric/bathymetric survey of the upper 4.6 miles of the San Marcos River system (hereafter referred to as the “San Marcos River”) and Spring Lake; (2) aquatic vegetation mapping overlay [coverage]; (3) 1- and 2-dimensional hydraulic modeling components; (4) vegetation specific vertical velocity profile modeling component; (5) temperature component; and (6) a module that integrates these component model outputs with the species specific response functions to assess fountain darter and wild-rice habitat quantity and quality with respect to depth, velocity, temperature and, in the case of the fountain darter, aquatic vegetation.

A GPS/sonar data collection technique was used to create a system wide morphometric representation with spatial resolution fine enough to support 2-D hydraulic modeling. Use of the 2-D hydraulic model logistically enabled spatial variability in vegetation type and distribution to be included in the habitat analysis and, to a lesser degree, in the hydraulic modeling of velocities. Additionally, 1-D water quality modeling was performed to determine the effects of spring discharge on water temperature concentrations. The various modeling components permitted a spatially explicit determination of water depth, mean column velocity, velocity at 15 cm above the channel bed, and water temperature throughout the San Marcos system at differing total spring discharges (15 to 170 cubic feet per second (cfs)). Combining these modeling results with mapped vegetation types and biological response functions permitted the development of predictive relationships for the target species. The modeling effort was implemented within a flexible analysis framework to permit alternative flow scenarios to be evaluated for assistance in making resource management decisions in the future. Data for Texas wild-rice are limited. The modeling assumptions for Texas wild-rice are probably not adequate to explain current wild-rice distribution in the river. Texas wild-rice modeling herein is a
heuristic endeavor focusing on a very limited number of physical habitat attributes. These models do not address any of the biological and physico-chemical interactions that surely have played a significant role in the current wild-rice distribution.

Predictions for the entire San Marcos River system were made regarding the amount and location of darter habitat availability at six discharges [flow rates] based on habitat suitability equations developed for the target species in the San Marcos River. Habitat modeling revealed that dams were a significant habitat factor in the San Marcos River system. For example, Spring Lake Dam has created much more wetted area in the San Marcos springs headwater area but habitats were converted from lotic to lentic. Spring Lake Dam has negated virtually all of modeled wild-rice habitat in Spring Lake for chosen flowrates due to decreased water velocity in much of the lake. Temperature was generally the limiting habitat variable for fountain darters while lack of vegetation also decreased modeled fountain darter weighted usable area in several reaches of the river. In some areas immediately upstream from dams habitat may be unsuitable for wild-rice due to low water velocities created by dam backwaters and by excessive depths caused by impoundment and dredging.

The habitat model was also used to evaluate the effect of different flow splits at Cape’s Dam, which is in need of repair. The USFWS has expressed interest in helping to fund such repairs if improvements could be made to the structure to actively partition flows between the main channel and the mill race channel and optimize fountain darter and wild-rice habitat. The San Marcos habitat model was used to conduct a preliminary examination potential effects of partitioning flow on water temperatures, depths, and velocities in affected areas. These modeled data were then used in conjunction with U.S. Army Corps of Engineers vegetation data to predict the resulting suitable habitat for the target species in each flow split scenario. Two flow split scenarios were run at each overall San Marcos Springs flowrate with ¾ total river flow partitioned down the main San Marcos River channel or alternatively down the Mill Race. The temperature model revealed negligible changes in temperature due to active partitioning between the two channels. Wild-rice habitat benefited exclusively from diverting the majority of river flow down the main San Marcos River channel below Cape’s Dam at all modeled flow rates. Due to extensive drying of the main channel at the lowest modeled flow rates, depth and velocity for fountain darters benefited from diverting the majority of river flow (modeled as ¾ total river flow) down the mill race at low flow rates. In the event of very low flow (less than 30 cfs) and the need to make the best out a dire situation, considerations should be given to maintaining native macrophytes like wild-rice, which has habitat value for fountain darters.

Habitat predictions for the fountain darter revealed distinctive discharge-dependent trends and should be considered as habitat limitations imparted by physical and chemical variables. Future analyses may incorporate plant community alterations to reflect other vegetation states/conditions. Additional biological interactions (such as predation, competition, parasitism, etc.) or changes in water quality or system flow inputs that may affect species populations are not considered within this analysis.
# Table of Contents

**EXECUTIVE SUMMARY**

**INTRODUCTION**

- San Marcos River System
  
- Endangered Species

- San Marcos Springs

- Historical Hydrology

- System Alterations

- Fountain Darters (*Etheostoma fonticola*)
  
- Historical San Marcos Distribution

- Threats to Fountain Darters

- Texas Wild-Rice (*Zizania texana*)
  
- Threats to Wild-rice

- Instream Flow Habitat Analysis Method

- Modeled Flow Rates

- Fountain Darter Habitat Criteria
  
  - Depth Habitat Criteria
  
  - Velocity Habitat Criteria

  - Temperature Habitat Criteria

  - Vegetation Habitat Criteria

- Wild-rice Habitat Criteria
  
  - Soils

  - Water Quality

  - Water Depth

  - Water Velocity

**Data Collection**

- Vegetation Mapping

- Surveying

  - Elevation Survey

  - Dam Survey

  - Shallow Areas Survey

- Global Positioning System/Sonar System Bathymetry Data

  - GPS/Sonar Sampling Method

  - Water Surface Elevations

  - Water Temperatures

- Habitat Modeling

  - 2-Dimensional Hydraulic Modeling

  - 1-Dimensional Hydraulic Modeling

- Water Quality Modeling
DISCUSSION

System-Wide Fountain Darter Weighted Usable Area

Spring Lake
Rio Vista
Mill Race
State Hatchery A
State Hatchery B
Lower San Marcos A
Lower San Marcos B

System-Wide Wild-rice Weighted Usable Area

Spring Lake
Rio Vista
Above Cape’s
Mill Race
State Hatchery A
State Hatchery B
Lower San Marcos A
Lower San Marcos B

Cape’s Dam Flow Split Temperature Effects

Cape’s Dam Flow Split Fountain Darter and Wild-rice Habitat Effects

RESULTS

System-Wide Fountain Darter Habitat Modeling
System-Wide Wild-rice Habitat Modeling
Cape’s Dam Flow Split and Fountain Darter and Wild-rice Habitat Optimization
GIS Analysis

REFERENCES CITED
ABBREVIATIONS

cfs  Cubic feet per second
GIS  Geographic information system
HSI  Habitat suitability index
HUC  Habitat utilization curve
INSE Institute of Natural Systems Engineering
MGD  Million gallons per day
tSMSf Total San Marcos Springs flowrate
USACE U.S. Army Corps of Engineers
USFWS U.S. Fish and Wildlife Service
USU  Utah State University

List of Figures

Overview of the San Marcos Modeling Sections
San Marcos Instream Flow Study Sections
San Marcos fountain darter depth habitat utilization curve with histogram
San Marcos fountain darter velocity habitat utilization curve with sampling histogram
Fountain darter habitat suitability index by water temperature
Wild-rice habitat suitability index values by depth
Wild-rice habitat suitability index values by velocity
San Marcos QUAL2EU water quality modeling reaches with USFWS Stowaway temperature logger positions marked (blacked-out circles)
QUAL2EU water temperature calibration results at the City Park temperature logging station
QUAL2EU water temperature verification results at the City Park temperature logging station
List of Tables

1. Modeled San Marcos Springs flows ................................................................................................
2. USFWS San Marcos database fountain darter distributions and HUC values by depth ..............
3. USFWS San Marcos database fountain darter distributions and HUC values by velocity ..........
4. Fountain darter presence to absence ratio assignment and associated suitability index.............
San Marcos Texas wild-rice habitat suitability values by depth........................................................
7. Modeled fountain darter weighted usable area by total San Marcos Springs flow .................
8. Modeled wild-rice weighted usable area by total San Marcos Spring flow.............................
9. San Marcos Cape’s Dam flow split fountain darter and wild-rice habitat modeling results with optimal flows in bold for each species.................................................................
10. Summary of low flow (< 135 cfs) habitat-limiting factors for Texas wild-rice and fountain darters in the San Marcos River system habitat model..................................................
INTRODUCTION

San Marcos River System

The San Marcos River originates from San Marcos Springs in Spring Lake, San Marcos, Hays County, Texas. The river flows 4.6 miles downstream to a confluence with the Blanco River (Figure 1) and continues for another 71.5 miles where it joins the Guadalupe River. This report focuses on the first 4.6 miles of river and any references to the San Marcos River in this report refer to the first 4.6 miles of river. Total San Marcos Springs flows will be referred to by the abbreviation ‘tSMSf’ to avoid confusion in the Cape’s Dam area where river flow is split in two, partitioning flow down the mill race and the main San Marcos river channels.

Endangered Species

The San Marcos River is home to several endangered species. *Etheostoma fonticola* (fountain darters) are found only in the San Marcos and Comal Rivers and *Zizania texana* (Texas wild-rice) is found only in the San Marcos River. *Gambusia georgei* (San Marcos gambusia) was first described in the San Marcos River but collections since 1982 have failed to locate any specimens (Edwards 1999, USFWS 1996) and this species may already be extinct. Two salamander species also are associated with San Marcos Springs, *Eurycea nana* (San Marcos salamander) and *Typhlomolge (Eurycea) rathbuni* (Texas blind salamander). San Marcos salamanders are endemic to Spring Lake and the areas immediately downstream. Texas blind salamanders are subterranean, found in the Edwards aquifer in Hays County. This species also can be found in Spring Lake in and near the outflows of several of the deeper springs.

This report addresses habitat modeling performed on the San Marcos River for fountain darters and Texas wild-rice.

San Marcos Springs

San Marcos Springs flow from the San Antonio section of the Edwards aquifer along the San Marcos Springs fault where an underground barrier of Austin chalk and Taylor marl force the water to the surface (W.F. Guyton and Assoc. 1979). More than 200 springs emanate from three large fissures and many smaller openings in the bottom of Spring Lake (Brune, 1981). The San Marcos Springs are the second largest springs in Texas in terms of discharge.

W.A. McClintock (1930) described the San Marcos Springs at the time:

“.. These springs gush from the foot of a high cliff and boil up as from a well in the middle of the channel. One of these, the first you see in going up the stream, is near the center, the channel is here 40 yards wide, the water 15 or 20 feet deep, yet so strong is the ebullition of spring, that the water is thrown two or three feet above the surface of the stream. I am told that by approaching it in canoe, you may see down in the chasm from whence the water issues. Large stones are thrown up, as you’ve seen grains of sand in small springs, it is unaffected by the driest season... It is about 60′ wide and 3′ deep on an average with a current of not less than 10 to 15 miles per hour. Great numbers of the
finest fish; and occasionally an alligator may be seen sporting in its crystal waters.”

Historical Hydrology

The period of record for daily mean discharge for the San Marcos River by the USGS begins May, 1956. (USGS station 08170500). Minimum spring discharge for this period was 46 cfs on August 15 and 16, 1956 (Gandara et al. 2000). Maximum flood flows have been estimated at up to 21,500 cfs in October 1998 (Slade and Persky 1999). Spring water is thermally constant at an average of 71.6°F with temperature fluctuations generally less than 1°F (W.F. Guyton and Associates 1979). Spring flows have been adversely impacted by increased withdrawals from the aquifer in recent years, causing low spring flows with greater frequency during less severe droughts. San Marcos Springs discharge (daily mean) of less than 100 cfs were recorded in 1989, 1990, 1996, and 1998 and may occur again this summer (2000).

System Alterations

The San Marcos River system has largely been altered from its natural state by several dams and flow inputs. Spring Lake dam was built near the headwaters in 1849 (ERPM 1999). The dam has dramatically changed the nature of the headwaters area by creating a deep, backwater area. Water depths over the San Marcos Springs fissures/orifices are now as deep as 25 feet. Sink Creek enters Spring Lake from the northeast and Spring Lake Dam inundates the lowest reach of Sink Creek channel for 0.6 miles. This backwater area is known as the ‘Slough’ and contains half of the Spring Lake wetted area (48,700 yd² of 96,600 yd² total). Sink Creek flows are typically below 4 cfs and resulting slough water velocities are very low. Water exits the lake via spillways on both sides of Spring Lake Dam. Over the years, Spring Lake Dam has become undermined with numerous leaks and is now a candidate for an emergency rebuild. Spring Lake Dam has a head of about 11.5 feet at normal flows.

Rio Vista Dam is located 0.95 miles downstream of Spring Lake Dam. This smaller, notched dam is a popular tubing, kayaking and swimming site and has a head of about 5 feet at normal flows.

Cape’s Dam is located 1.6 miles downstream of Spring Lake Dam and partitions San Marcos River flow down the ‘mill race’ and the main San Marcos River channel. At normal flows, the mill race carries approximately 30 percent of river flow. The mill race flows 0.36 miles and the main channel flows 0.65 miles before they join together at the mill race outfall which is a multi-notched weir with a head of about 11.5 feet at normal flows. Cape’s Dam has a head of about five feet at normal flows.

A.E. Wood State Fish Hatchery is located adjacent to the main channel 2.1 miles below Spring Lake Dam with a discharge point 300 feet upstream of the mill race/main channel confluence (Figure 1). The hatchery draws and discharges river water for its operations and has recently applied for a 5 million gallon per day discharge permit. Hatchery effluent has been noticeably more turbid than San Marcos River water. A treatment system currently under construction is expected to dramatically improve discharge quality as well as reduce the risk of fish escapement.

The City of San Marcos municipal wastewater treatment plant discharges 2.8 miles below Spring Lake Dam and is permitted to discharge 9 million gallons per day (MGD).

Cumming’s Dam is located 5.1 miles downstream of Spring Lake Dam and is a major
structure with an estimated 18 ft head at normal flows. It has an effect on water surface elevations for the majority of river upstream to the City of San Marcos wastewater treatment plant.

1. Figure 1. Overview of San Marcos habitat modeling sections. The Blanco River and the area below the confluence down to Cumming’s Dam are not included in this report.

**Fountain Darters (Etheostoma fonticola)**

Fountain darters (*Etheostoma fonticola*) are endemic to the Comal and upper San Marcos rivers. The Comal population was extirpated, most likely due to low flow conditions in 1956 when the Comal Springs stopped flowing for about six months. Fountain darters were restocked by Schenck and Whiteside (1977) with fountain darters from the San Marcos River in 1975 and 1976. The fountain darter is federally listed as endangered (Federal Register 35:16047; October 13, 1970). It is also listed by the State of Texas as endangered.

Discussion of fountain darter habitat is contained in the methods section of this report.

**Historical San Marcos Distribution**

Schenck and Whiteside (1976) collected fountain darters in the San Marcos River as far downstream as the City of San Marcos wastewater treatment plant outfall. They give two possible reasons for the lack of fountain darters below this point: the effluent from the sewage treatment plant and/or Cumming’s Dam effects “which probably changed the habitat and could have eliminated the species from this area... Water in this segment is fairly deep and the river
banks are sharply cut... restrict[ing] the growth of many types of vegetation which *E. fonticola* prefers in the upper reaches of the river."

**Threats to Fountain Darters**  
Fountain darters occupy areas with constant water temperatures, undisturbed stream floor habitats, a mix of submergent vegetation in part for cover, clear and clean water, a food supply of living organisms and most importantly, adequate springflows (USFWS 1996). Since they are found only in the Comal and upper San Marcos River systems, any habitat loss in these systems may have a large impact on fountain darters.

**Texas Wild-Rice (*Zizania texana*)**  
Texas wild-rice, hereafter referred to as wild-rice, is an aquatic grass endemic to the upper San Marcos River, Hays County, Texas (Emery and Guy 1979). Wild-rice was first collected by G.C. Nealley in 1892 (U.S. Herbarium Sheet 979361) but only recognized as a distinct species forty-one years later (Hitchcock 1933).  
Wild-rice populations have declined dramatically in the forty-five years since its description. It is listed as an endangered species (Federal Register 43:17910-17916). Emery and Guy (1979) attribute the present condition of the species to environmental rather than cytological factors. Readers are referred to work by Silveus (1933), Beaty (1975), Emery (1979), Emery and Guy (1979), Vaughan (1986), Power (1990), Poole (1995), Poole and Bowles (1996), and Poole and Bowles (1999) for further information on wild-rice biology. Discussion of wild-rice habitat is contained in the Methods section of this report.

**Threats to Wild-rice**  
Threats to wild-rice include dam construction, erosion, siltation, aquatic vegetation removal, stream channelization and introductions of exotic species (Poole and Bowles 1996). Emery (1981) lists additional threats as introduction of the exotic small mammal, nutria, introduction of the exotic aquatic plant *Hydrilla* sp., increasing recreational use of the river, severe flooding, and a total absence of sexual reproduction in the native population.

**Instream Flow Habitat Analysis Method**  
Previous studies had shown vegetation, water temperatures, depths and velocities to be important habitat variables for the fountain darter in habitat modeling performed on the Comal River (Hardy et. al. 1998). These studies and a San Marcos sampling database across varying flows (1994, 1995, and 1996) were analyzed to create fountain darter habitat suitability curves. A habitat modeling approach similar to that used by Hardy et. al. (1998) was used to model these variables at a range of flows within the San Marcos River system in order to quantify the effects of decreasing flow on fountain darter habitat. Habitat information on Texas wild-rice is more limited. Analysis of wild-rice research data provided water depth and velocity habitat profiles, and these profiles were also used in the San Marcos habitat model to identify a range of depths and velocities assumed to represent suitable wild-rice habitat. Some assumptions about habitat requirements for Texas wild-rice may be inaccurate and may change as more information becomes available.

Traditional aquatic habitat modeling has been 1-D based (PHABSIM, Bovee 1978) and
did not allow spatially intensive, detailed hydraulic modeling of basic river features such as eddies, backwater areas, multiple channels, or spring source inputs. Two dimensionally-based (2-D) hydraulic modeling allows all of these features to be modeled, as well as real-coordinate system overlays of diverse habitat information such as vegetation type and water temperature and incorporation of differing hydraulic roughness due to individual vegetation species, resulting in more accurate hydraulic results and therefore habitat results. Recent advancements in two-dimensional (2-D) hydraulic modeling models and interfaces have allowed easier use of and access to 2-D hydraulic models, a tool which had been little used (LeClerc et. al. 1995).

The FESWMS hydraulic model was used to provide 2-D depths, velocities and water surface elevations. Calibration data was used from field sources or the 1-D HEC-RAS hydraulic model. Two-dimensional hydraulic grids and results were imported into the ArcView geographic information system (GIS) and overlaid onto an AutoCAD edge-of-water map provided by the Texas Parks and Wildlife Department (TPWD). The 1-D QUAL2EU water quality model was then used to quantify water temperatures at the desired system flow rates and these results were imported into ArcView (version 3.1, ESRI) and overlaid on the hydraulic mesh. U.S. Army Corps of Engineers (USACE) and University of North Texas staff have periodically monitored and mapped system vegetation using global-positioning-system (GPS) based methods and produced a 2-D vegetation map for the entire San Marcos River system. This data was provided to the INSE in an ArcView format and overlaid on the hydraulic grid for habitat cell vegetation assignment.

ArcView Avenue programs were written to automatically combine the desired flow rate hydraulic information from all modeled flow rates onto the hydraulic grid, combine that information with temperature interpolations and static vegetation mapping, compute the resulting weighted usable area (WUA) in each hydraulic cell for both fountain darter and wild-rice habitat, and store the information in dBase format.

WUA refers to the method by which the area in a hydraulic cell or area is multiplied by weighting factors that are in turn a function of habitat variable values within that cell or area. For the fountain darter habitat evaluation, the total area in each hydraulic/habitat cell was multiplied by a temperature, vegetation, depth and velocity weighting factor. Due to more limited wild-rice habitat information, the total area in each hydraulic/habitat cell was only multiplied by depth and velocity weighting factors. All weighting factors had magnitudes ranging from zero to one. Wild-rice and fountain darter WUA values should not be compared directly to each other due to the fact that the fountain darter WUAs were produced by multiplying the total cell area by four weighting factors as opposed to the two weighting factors used for wild-rice. Conclusions may be drawn from comparison of the two species analyses if the difference in number of WUA weighting factors is considered.

The resulting total WUA for each habitat modeling section at each modeled flow rate was then tabulated and plotted against flow rate to determine the effects of flow rate on fountain darter and wild-rice habitat.

**Modeled Flow Rates**

A decline in spring discharge poses a threat to fountain darter and wild-rice habitat. San Marcos Springs flow rates near and below the mean discharge were modeled in order to quantify the effects of declining flows. Flow rates modeled are shown in Table 1.
Table 1. Modeled San Marcos Springs flows. Flow split scenario 1 was used for modeling the entire San Marcos River system at normal flow split conditions with the majority of river flow at Cape’s Dam going down the main San Marcos River channel. Flow split scenario 2 was used to model the system with the majority of river flow at Cape’s Dam going down the mill race.

<table>
<thead>
<tr>
<th>San Marcos Springs Flow Rate Modeled (cfs)</th>
<th>Mill Race channel (cfs)</th>
<th>Main channel from Cape’s Dam to mill race/main channel confluence only (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15, Flow split scenario 1</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>15, Flow split scenario 2</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>30, Flow split scenario 1</td>
<td>10</td>
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</tr>
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<td>30, Flow split scenario 2</td>
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<tr>
<td>65, Flow split scenario 2</td>
<td>45</td>
<td>20</td>
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<td>100, Flow split scenario 2</td>
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<td>95</td>
<td>40</td>
</tr>
<tr>
<td>170, Flow split scenario 1</td>
<td>60</td>
<td>110</td>
</tr>
<tr>
<td>170, Flow split scenario 2</td>
<td>110</td>
<td>60</td>
</tr>
</tbody>
</table>
METHODS

San Marcos Biological Sampling Database
To develop a better understanding of fountain darter habitat associations in the San Marcos system, a stratified random sampling procedure was employed to sample 2 m² areas in uniform meso-scale habitat types using a rectangular drop net structure designed and built for the sister study on the Comal River. Meso-scale habitat types (strata) corresponded to delineated sections in Figure 2. Samples were collected during the summer 1994, fall 1994, winter 1994-1995, spring 1995, and late summer 1996. Samples were collected in areas up to water depths of 4 ft throughout in various parts of Spring Lake, the San Marcos River downstream of Spring Lake (to its confluence with the Blanco River). For each collection location, a depletion sample of all fish species was accomplished and fish type, numbers and lengths were recorded. At each location, vegetation type, vegetation height and areal coverage, substrate type, mean column velocity and velocity at 15 cm above the bottom, water temperature, conductivity, pH, and dissolved oxygen were recorded. Vegetation type, vegetation height, and substrate were also noted for all adjacent 3 meter cell areas at each sample location. Fountain darters were measured and released at the sample location. Other fish were either (1) preserved in the field and identified in the lab or (2) identified, measured and released. All live ramshorn snails were preserved and measured. Crayfish were either measured and released or preserved. Other macroinvertebrates were included in preserved samples. Physical and chemical characterization were made for each selected location the day prior to or on the same day as sampling. Direct observations of darters using scuba was employed for water deeper than 4 ft in the river downstream of Spring Lake.

Fountain Darter Habitat Criteria
The USFWS fountain darter biological sampling database was analyzed to determine San Marcos-specific depth, velocity and vegetation criteria for use in habitat modeling.

Depth Habitat Criteria
The USFWS San Marcos biological sampling database was analyzed to create fountain darter depth habitat suitability curves. Presence to absence ratios were approximately the same for all sampling periods (July 1994, October 1994, January 1995, April 1995, and September 1996) and these sampling period data were grouped together. Nelson (1984) describes using a histogram of fish observations and normalizing it to form a habitat utilization curve (HUC). This method was used to create depth HUCs for San Marcos.

Depth data were divided into five depth classes: 0-1 ft, 1-2 ft, 2-3 ft, 3-4 ft, and >4 ft depths (Table 2) and a depth class histogram was generated (Figure 2). The resulting curve peaked at the 2-3 foot level and decreased at greater depths. INSE research engineers have scuba-dived in the sister Comal River system and observed fountain darters at depths up to fourteen feet. The sampling method used in the San Marcos system was only able to effectively sample at depths up to four feet and it is
Figure 2. San Marcos Instream Flow Study Sections
possible that sampling success deteriorated at depths exceeding three feet. Based on these facts and hypotheses, the INSE felt that depths above three feet were suitable for fountain darter habitat and the habitat utilization curve was extended at the HUC = 1.0 level for depths greater than three feet. The final HUC is shown in Figure 3.

Table 2. USFWS San Marcos database fountain darter distributions and HUC values by depth.

<table>
<thead>
<tr>
<th>Depth Class (ft)</th>
<th>Depth Range (ft)</th>
<th>Number of Observations</th>
<th>Raw Habitat Value</th>
<th>Modified Habitat Value</th>
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<tbody>
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<td>0-1</td>
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<td>1.000</td>
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<td>0.338</td>
<td>1.000</td>
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<tr>
<td>4</td>
<td>&gt;4</td>
<td>7</td>
<td>0.044</td>
<td>1.000</td>
</tr>
</tbody>
</table>

2. Figure 3. San Marcos fountain darter depth habitat utilization curve with histogram.

Velocity Habitat Criteria

The USFWS San Marcos biological sampling database was analyzed for fountain darter HUC values in the same manner used to analyze for depth HUC curves. Results are shown in Table 3 and Figure 3. Since the USFWS biological sampling covered nearly all water velocities found in the San Marcos River system, no adjustments in the velocity HUC curve were deemed necessary.
Table 3. USFWS San Marcos database fountain darter distributions and HUC values by velocity.

<table>
<thead>
<tr>
<th>Velocity Class</th>
<th>Velocity Range (ft/s)</th>
<th>Number of Observations</th>
<th>Raw Habitat Suitability Index Value</th>
<th>Modified Habitat Suitability Index Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0-0.5</td>
<td>249</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>1</td>
<td>0.5-1</td>
<td>0</td>
<td>0.000</td>
<td>0.470</td>
</tr>
<tr>
<td>2</td>
<td>1.0-1.5</td>
<td>43</td>
<td>0.173</td>
<td>0.200</td>
</tr>
<tr>
<td>3</td>
<td>1.5-2</td>
<td>3</td>
<td>0.012</td>
<td>0.065</td>
</tr>
<tr>
<td>4</td>
<td>2-2.5</td>
<td>10</td>
<td>0.040</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Temperature Habitat Criteria

In 1997, Hardy et al. (1998) developed a temperature curve for fountain darter habitat in the Comal River. This same temperature curve is utilized for the San Marcos habitat model. The section in the final report for the Comal River fountain darter habitat modeling project is reproduced here:
Recent studies (Bonner et al., 1998) have provided new information regarding the effects of temperature on fountain darters at several life stages. This literature along with other references indicates that temperature needs to be considered as a macro habitat variable important for good fountain darter habitat.

Known studies providing temperature data for the fountain darter are broken down after Armour (1993) in Table 4.

Table 4. Breakdown of available information on thermal regime effects on the fountain darter.

<table>
<thead>
<tr>
<th>Life stage</th>
<th>Reference</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eggs</td>
<td>Brandt et. al. (1993)</td>
<td>Non-viable eggs produced at 37.4°F and 86°F.</td>
</tr>
<tr>
<td>Eggs</td>
<td>Bonner et. al. (1998)</td>
<td>Lowered egg production at 80.6°F and 84.4°F than at 57.2, 62.6, 68, 73.4 and 25°F.</td>
</tr>
<tr>
<td>Eggs</td>
<td>Bonner et. al. (1998)</td>
<td>Percent hatch was lower at temperatures of 77, 80.6 and 29 °F than at temperatures of 57.2, 62.6, 68 and 73.4°F.</td>
</tr>
<tr>
<td>Larvae</td>
<td>Bonner et. al. (1998)</td>
<td>Minimum LC50 at 38.8°F</td>
</tr>
<tr>
<td>Larvae</td>
<td>Bonner et. al. (1998)</td>
<td>Maximum LC50 at 89.4°F</td>
</tr>
<tr>
<td>Larvae</td>
<td>Bonner et. al. (1998)</td>
<td>Larval production noticeably greater at temperatures of 62.6, 68 and 73.4°F than at temperatures of 57.2, 77, 80.6 and 84.4°F.</td>
</tr>
<tr>
<td>Adult</td>
<td>Brandt et. al. (1993)</td>
<td>Critical thermal maximum at 94.6°F</td>
</tr>
<tr>
<td>Spawning</td>
<td>Brandt et. al. (1993)</td>
<td>Viable spawning occurred from 42.8°F to 80.6°F.</td>
</tr>
</tbody>
</table>

*Coutant (1972) recommends a 2°C safety margin to be subtracted from the short term maximum temperature (STM) to derive a predicted value for 100% survival.*

The fountain darter breeds year round (Schenk, 1975) and therefore the most conservative minimum and maximum temperature must be used in evaluating temperature regimes for suitability. The fact that the fountain darter is endangered, found only in two river systems, potentially parasitized and threatened by introduced species effects only reinforces the need to approach the modeling and evaluation of fountain darter habitat in a conservative manner. Therefore, the data in Table 4 were used to produce the following fountain darter thermal regime habitat suitability index (HSI), shown in Figure 5.
The lower suitable temperature cutoff is based on data from Bonner et. al. (1998). An increase to a suitability index value to 1.00 at 62.6°F is used since 62.6°F is the lowest temperature at which larval production was unaffected. From 62.6°C to 73.4°F, no adverse effects on darters are known, based on the available literature. Percent hatch was lower at 77°F than at temperatures of 73.4°F and lower (Bonner et. al., 1998). The midpoint of these two temperatures, 75.2°F, was chosen as the maximum temperature with a habitat suitability of 1.00.

The reduction in suitability values near 77°C and ending at 80.6°F is due to observed reduced egg production and percent hatch at these temperatures. From 80.6°F to 84.38°F, a suitability index value of 0.1 is assigned to habitat as it is felt that this habitat, while far from ideal for all fountain darter life stages, still holds some value for the fish. The 84.38°F upper temperature cutoff was arrived at by using a 2°C pad (Coutant, 1972) on the larval LC50 of 89.6°F.

**Vegetation Habitat Criteria**

The USFWS San Marcos biological sampling database contained 290 sample cells with recorded vegetation type. These data were separated by species and analyzed to determine the ratio of cells with fountain darters present to the number of cells with fountain darters absent for each vegetation species. Vegetation types were then assigned to one of five categories based on
the presence/absence ratio. Table 5 shows these categories, presence to absence ratio ranges and associated habitat suitability index.

Table 5. Fountain darter presence to absence ratio assignment and associated suitability index.

<table>
<thead>
<tr>
<th>Category</th>
<th>P/A Ratio</th>
<th>Habitat Suitability Index Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.2-0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>0.4-0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>0.6-0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>0.8-1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Of the twenty vegetation species collected in the USFWS biological sampling, nine vegetation species had less than five sample cells. Due to the lack of information existing on these nine vegetation species as well as other, totally un-sampled species present in the San Marcos system, a need existed for additional data to assign these vegetation species an HSI value. For this purpose, the USFWS Comal biological sampling database was referenced and vegetation categories and HSI values were assigned based on presence to absence ratios. If sufficient (>9 sample cells) data existed in the San Marcos database then HSI values were assigned based on the San Marcos database. If sufficient cells did not exist, HSI values based on the USFWS Comal biological sampling database were assigned if possible.

Species with sufficient USFWS San Marcos biological sampling database cell counts were: *Sagittaria* sp., *Utricularia* sp., *Typha* sp., reeds, *Ludwigia* sp., *Vallisneria* sp., *Egeria/Elodea* sp., *Moss-bryophyta* sp., *Hydrilla* sp., *Ceratopteris* sp., *Justicia* sp., and ‘evident green leaves’. Species with insufficient USFWS San Marcos database cell counts that were assigned USFWS Comal database vegetation HSI values were: green algae (includes non-algae such as the moss *Amblystegium riparium*, other), filamentous green algae and blue-green algae. Species lacking any USFWS San Marcos database cell counts and assigned USFWS Comal database HSI values were: *Hydrocotyle* sp., spike rush, ‘algae on rocks’, *Myriophyllum* sp., bare substrate, *Riccia* sp., *Cabomba* sp., and roots. Species which had insufficient sample cell counts in both USFWS biological sampling databases were: watercress, ‘minimum green algae’, *Hygrophiila* sp., red algae, *Narcissus* sp., *Chara* sp., *Eleocharis* sp., *Ceratophyllum* sp., *Heteranthera* sp., *Taro* sp., *Potamogeton* sp., *Limnophila* sp., and *Zizania* sp. These species were not assigned HSI values.

The USACE vegetation mapping database did not contain all of the afore-mentioned species so only those species (plus the no-vegetation designation) present in the USACE database were used in this analysis. Table 6 shows the final vegetation species HSI values.
It is interesting to compare the INSE habitat rankings to earlier fountain darter vegetation preferences outlined by Schenck and Whiteside (1976). They list preferred vegetation types as: *Rhyzoclonium* sp., *Hydrilla* sp. (INSE HSI = 0.8) and *Ludwigia* sp. (INSE HSI = 0.6). Vegetations less preferred but still containing fountain darters were: *Potamogeton* sp. (INSE HSI = 0.6), *Vallisneria* sp. (INSE HSI = 0.6), and *Zizania* sp. (INSE HSI = 0.6). Schenck and Whiteside’s (1976) sample areas with no vegetation (INSE HSI = 0.2) are described as not containing any fountain darters. Diving observations in the Comal River by INSE research staff has documented the presence of fountain darters in non-vegetated areas, albeit at lower densities.

### Wild-rice Habitat Criteria

Available research for delineating important variables for Texas wild-rice is more limited. Habitat criteria for wild-rice was generated through examination of several papers, descriptions and studies. The Section 6 report by Poole and Bowles (1996) was used in part to provide velocity and depth criteria with Table 6. TPWD data, including mean depths and velocities, were particularly useful. Notes taken at the Conservation Breeding Specialist Group wild-rice workshop held in San Marcos, Texas, in November 1996 were also used (CBSG 1997).

Wild-rice data from Texas Wildlife and Parks Department data shows wild-rice to occupy moderately-coarse to coarse sandy soil sites (Poole and Bowles 1996). This is in contrast to

<table>
<thead>
<tr>
<th>U.S. Army Corps of Engineers Species</th>
<th>San Marcos Habitat Suitability Index Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare Substrate (no vegetation)</td>
<td>0.2</td>
</tr>
<tr>
<td><em>Hydrocotyle</em> sp.</td>
<td>0.2</td>
</tr>
<tr>
<td><em>Myriophyllum</em> sp.</td>
<td>0.2</td>
</tr>
<tr>
<td><em>Cabomba</em> sp.</td>
<td>0.4</td>
</tr>
<tr>
<td><em>Sagittaria</em> sp.</td>
<td>0.4</td>
</tr>
<tr>
<td><em>Ceratophyllum</em> sp.</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Eleocharis</em> sp.</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Heteranthera</em> sp.</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Hygrophila</em> sp.</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Limnophila</em> sp.</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Ludwigia</em> sp.</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Narcissus</em> sp.</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Potamogeton</em> sp.</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Taro</em> sp.</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Vallisneria</em> sp.</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Zizania texana</em> sp.</td>
<td>0.6</td>
</tr>
<tr>
<td><em>Ceratopteris</em> sp.</td>
<td>0.8</td>
</tr>
<tr>
<td><em>Egeria (Elodea)</em> sp.</td>
<td>0.8</td>
</tr>
<tr>
<td><em>Hydrilla</em> sp.</td>
<td>0.8</td>
</tr>
<tr>
<td><em>Justicia</em> sp.</td>
<td>1.0</td>
</tr>
<tr>
<td><em>Nuphar</em> sp.</td>
<td>1.0</td>
</tr>
</tbody>
</table>
study results by Power and Fonteyn (1990) that found clay to be the preferred substrate for wild-rice although Powers (1990) notes that in the wild: “Most *Z. texana* is presently found in sandy/gravelly soil in the mid-channel of the San Marcos River.” Vaughan (1986) found “Soil type had a minimal effect…”

Due to lack of clear consensus as well as the fact that no detailed substrate maps exist for the San Marcos system, this habitat variable was not analyzed or used in this study.

**Water Quality**

Poole and Bowles (1996) found wild-rice to occur at sites with high water clarity. They also found that salt, Ca and SO\(_4\) concentrations were higher in sediment at non-wild-rice transects and hypothesized that this was due to urban and agricultural run-off effects and the City of San Marcos Wastewater treatment plant effluent impacts to water quality.

Dissolved oxygen concentrations were found to be significantly different between wild-rice and non-wild-rice areas in TPWD data (Poole and Bowles, 1996) but both values were at oxygen saturation. Average turbidity was significantly higher for non-wild-rice transects in their study.

**Water Depth**

Poole and Bowles’ wild-rice depth 95% confidence intervals were 1.97 to 3.14 ft while non-wild-rice confidence intervals were 4.19 to 7.64 feet for data taken in May and August 1994 and January 1995. These averaged confidence interval values are taken from data sets that showed significant differences. Poole and Bowles (1996) state that, “rice transects were found to be shallower (≤ 1 meter) and with considerably faster current velocities compared to non-rice transects sampled where the water depth was greater (≥ 1.7 meters) and where the current velocities were slower.”

At the CBSG workshop, Paula Powers and Jackie Poole both gave approximate optimal depth and velocity envelopes for wild-rice during wild-rice working group discussion. From the working group notes:

“...habitat characterization work does show some information about [depth habitat] and so do observations. At more than 1.5 meters, the stands do not do as well. The average depth is 0.5 to 0.6 meters, which may not mean anything. Below 0.2 meters (8 inches) or 0.3 meters (about 12 inches) other limiting factors come into play, such as predation, erosion, recreational impacts, and normal water level fluctuations, etc.”

Vaughan (1986) found individual wild-rice stands grown in depths greater than 0.66 feet were significantly larger (P<0.05) than those in depths less than 0.66 feet. Silveus (1933) describes wild-rice as growing in water from one to seven feet deep. Much of the literature on depth of stands is qualitative in nature and is subject to interpretative error, particularly regarding the delineation of optimum, minimum, and maximum tolerances. Caution should be exercised in using this information in recommendations for conserving the species.

The above information was condensed to create the wild-rice depth habitat suitability curve, shown in Figure 5.
Table 6 from Poole and Bowles’ (1996) report showed average wild-rice stand velocity 95% confidence intervals of 0.94 ft/s to 2.32 ft/s while non-wild-rice transects had average 95% confidence intervals of 0.20 ft/s to 0.73 ft/s for data taken in May and August 1994 and January 1995. Non-wild-rice areas sampled clearly had lower velocities than wild-rice areas.

5. San Marcos Texas wild-rice habitat suitability values by depth.

From the CBSG (1997) notes:

“Velocities were discussed. Jackie thinks velocity in transect habitat analysis for wild-rice stands was 0.3–0.6 m/sec = maybe 1.7 feet/sec at the high end. This was higher than non-rice areas in the river... Paula Power suggested that 0.2 meters per second is probably too low. She agrees with Jackie that optima is probably 1 to 1.5 feet per second range.”

Silveus (1932) describes wild-rice habitat as growing “often in swiftly running currents.”

The above sources were entered into a spreadsheet and average values for minimum and maximum velocities calculated to create the wild-rice velocity HSI curve shown in Figure 6.
The information on which the HSI index curve is based is highly qualitative. This curve should be refined in the future when more quantitative information on the species is available from studies currently being initiated.

Figure 7. Texas wild-rice habitat suitability index values by mean column water velocity.

Data Collection

Vegetation Mapping

Vegetation species and location were mapped throughout the San Marcos River system by Dr. Robert Doyle of the U.S. Army Corps of Engineers (currently of the University of North Texas) and Matt Francis of the University of North Texas based on a separate USFWS interagency agreement. This information was transferred to the INSE for use in San Marcos wild-rice and fountain darter habitat modeling. This mapping effort predated the October 1998 flood. Prof. Doyle will likely assess quantitative and qualitative differences in vegetation pre- and post-flood. Future modeling efforts will use the best and most recent information on vegetation.

Surveying

Elevation Survey

A system wide survey was performed in order to create a reliable system of elevation benchmarks on which to base geometric data. The survey started at Aquarena Springs at the
headwaters of the San Marcos River system and ran down to the Blanco – San Marcos River confluence. Multiple survey loops were performed to reach the confluence with each loop being closed to within 0.01 ft elevation accuracy. Two additional loops were performed to place staff gages on the Blanco River and on Cummings Dam.

Over 200 points were surveyed and multiple benchmarks were placed along the river. Benchmarks consisted of rebar driven into the ground, existing TPWD benchmarks, and marks placed on roads, sidewalks and dams. Benchmarks placed on this survey were used to place GPS equipment for bathymetrical data collection later in the study.

Staff gage elevations were surveyed during this process in order to provide accurate water surface elevation boundary condition information for the hydraulic models and for use in GPS/sonar data analysis.

**Dam Survey**

Spring Lake Dam, Rio Vista Dam, Cape’s Dam and points on Cumming’s Dam were surveyed to provide data for the creation of the 1-D hydraulic model.

**Shallow Areas Survey**

Bathymetrical GPS/sonar data collection was limited to water depths greater than approximately two feet. Numerous areas in the San Marcos River were shallower than this limit during data collection. INSE and USFWS personnel surveyed these shallow areas using total station surveying equipment. The river immediately below Spring Lake Dam, Rio Vista Dam, Cheatham/Houston Street Bridge, immediately above Interstate 35, and along the A.E. Wood State Fish Hatchery was surveyed using this method.

Survey data was processed and added to the GPS/sonar data set for use in generating the system bathymetry and hydraulic mesh.

**Global Positioning System/Sonar System Bathymetry Data**

In order to collect data to support 1-D, 2-D and water quality modeling for the San Marcos River system, an integrated Global Positioning System (GPS) Survey Total Station and Hydroacoustic Bottom Sounder was used to collect bathymetry data for the San Marcos River and Spring Lake. The GPS component is a Trimble 4400 Total Station. This system consists of two units, base and rover, to perform carrier phase ambiguity resolution in real time with on-the-fly initialization available for the rover unit. Each of the units contains an L1/L2 antennae, datalogger, and receiver/processor. In addition the rover unit is configured to output positional information in an ASCII output string format similar to the National Marine Electronic Association (NMEA) 0183 standard.

The base station was set up over a control point with published or known coordinates in the WGS-84 datum. This base unit dynamically calculates its position based on pseudo range information as broadcast from the GPS satellite vehicles (SV). The errors associated with these GPS measurements produce a randomized walk around the correct position of the control point. The base unit then undertakes a series of calculations to remove these errors. Correction information in then broadcast from a low power spread spectrum radio. The rover unit receives this correction information and applies it to the solution from broadcast information at the rover.
location to calculate the rover position in real time. Accuracy for the positional information is 1 cm or 1 ppm horizontally and 1.5 cm or 1 ppm vertically.

The hydro-acoustic bottom sounder used was a Simrad model EA501P. This echo sounder is a narrow (7.6), single beam, high frequency (200 kHz) unit. The nominal depth accuracy is 7 cm. The EA501P consists of a transducer, high gain amplifier, notebook computer, and power source. The transducer is the in water component to transmit and receive the sound signals. The amplifier has a 160 dB instantaneous dynamic range and is used to condition the outgoing pulse and perform highly accurate measurement of the strength of the return signal. The notebook computer provides the user interface via the parallel port to configure the various settings of the EA501P (e.g. ping rate, depth range, display settings). In addition algorithms for determination of water depth are implemented in the software. The GPS system is integrated via the serial port of the computer where the position information is read. Both the depth and the positional information are time tagged using the computers clock. Later the positional information is interpolated to determine the correct positional information for the depth reading.

**GPS/Sonar Sampling Method**

Due to concerns about damaging existing stands of wild-rice, GPS/sonar data gathering was conducted using a canoe in all sections of river above the City of San Marcos wastewater treatment plant. Two research engineers and/or technicians paddled the boat, traversing the river channel from side to side to produce a spatially dense data coverage. No stands of wild-rice currently exist below the City of San Marcos wastewater treatment plant and it was possible to mount the GPS/sonar unit to a custom mount on a flat-bottom boat with a motor. This setup was used to gather GPS/sonar data for that part of the system below the treatment plant and greatly reduced data collection time.

**Water Surface Elevations**

Detailed water surface elevation data was necessary to create stage/discharge relationships for the San Marcos River as well as for use in GPS/sonar data collection and hydraulic model calibration. In order to allow INSE/USFWS personnel to more easily collect such data, a system of staff gages was placed throughout the San Marcos River system.

Staff gages consisted of USGS gage plates with readings every 0.01 ft. These plates were attached to redwood planks and the planks were attached to cement walls currently in the system by use of a cement nail gun or were attached to steel fence posts and driven into the river bed.

A reference elevation for each staff gage was surveyed in and tied to the system-wide elevation survey. INSE/USFWS personnel would record the water level on nearby staff gages during each visit to the system and this data was entered into a stage-discharge database. This system has resulted in 113 water surface elevation readings to date.

**Water Temperatures**

In order to gather accurate water temperatures to support water quality modeling in the San Marcos River system, a system of water temperature sensors was necessary. Nine small Stowaway temperature sensors were deployed. Steel caging was constructed to protect the sensors from vandalism or river debris damage and short lengths of chain were welded to the
caging. The sensors were set to collect temperature every fifteen minutes during each 24 hour period. INSE and USFWS personnel placed the nine sensors up and down the length of the river and downloaded the data approximately every two and a half months. Downloaded data was stored for later use in water temperature model calibration and verification.

Habitat Modeling

2-Dimensional Hydraulic Modeling

Two-dimensional (2-D) hydraulic model was developed for the San Marcos River to provide habitat analysis with spatially explicit water depths and velocities. The U.S. Federal Highway Administration’s FESWMS model was used. This model assumes that water velocities in the vertical direction are negligible, which was true for the vast majority of the San Marcos River system.

To facilitate hydraulic computations, the San Marcos River system was broken up into six sections (Figure 1) titled Spring Lake, Rio Vista, Above Cape’s, Mill Race, State Hatchery A, State Hatchery B, Lower San Marcos A and Lower San Marcos B. Section boundaries were placed at hydraulically suitable points, typically immediately above dams or changes in bed elevation. Placement of the 2-D hydraulic sections formed the basis for habitat analysis sections.

The USACE vegetation map was overlaid on each 2-D hydraulic section and each cell within the mesh was assigned a material type based on vegetation species. Each vegetation species except Texas wild-rice had a unique hydraulic roughness value based on previous USFWS vegetation/vertical velocity profile data collections in the Comal River system. INSE/USFWS staff gage or surveyed water surface elevations at the upstream and downstream segment boundaries were then evaluated for each section and a calibration water surface elevation chosen for the boundary condition at the downstream end of the segment. Based on the date of the staff gage reading either a USGS or a INSE/USFWS San Marcos River flowrate was assigned as the upper boundary condition for the segment.

The 2-D hydraulic segment was then modeled with the calibration data and the resulting water surface profile compared to field data. Proportional adjustments were made to the hydraulic roughness, using an INSE C++ program that interfaced with FESWMS datasets, in order to bring the 2-D hydraulic model water surface elevations within 0.1 foot or less of the recorded field water surface elevations.

Once the model was calibrated, QUAL2E model flows were changed to those shown in Table 1. Downstream water surface elevations were assigned by staff gage-generated stage/discharge curves or from 1-D HEC-RAS generated water surface elevations, depending on the quantity of staff gage information available at the downstream boundary of each 2-D hydraulic segment. The calibrated model was next run at each of the six modeled flows (up to twelve modeled flows for the Cape’s Dam area) and the results were imported into dBase format for use in ArcView.

1-Dimensional Hydraulic Modeling

Where available, staff gage water surface elevation curves were used to provide boundary conditions for all modeled flows. The mill race and Rio Vista 2-D hydraulic modeling segments were problematic in that water surface calibration information was either sparse or did not
provide the necessary low flow data. To rectify this lack of calibration information a 1-D model, HEC-RAS, was used to estimate the necessary data.

A 1-D model was constructed for the mill race outfall and Rio Vista Dam based on survey information gathered by INSE and USFWS personnel. The model was calibrated to surveyed or staff gage INSE/USFWS water surface elevation data to within 0.01 foot water surface elevation and INSE/USFWS or USGS flowrate data and then modeled at the necessary flows to generate water surface elevations for use in 2-D hydraulic modeling boundary conditions.

Water Quality Modeling

In order to provide accurate water temperatures for the habitat analysis, the QUAL2EU 1-D water quality model was used. This model performs a heat balance that accounts for long and short wave radiation, convection and evaporation (USEPA 1987).

The San Marcos River system was split into twenty-one separate sections based on in-reach similarities (Figure 8). Each section was divided into elements 100 feet long. Flow was input into the model in the Spring Lake slough area, main San Marcos Springs area in Spring Lake, from the A.E. Wood State Fish Hatchery and the City of San Marcos wastewater treatment plant.
**Calibration and Verification Data**

The INSE obtained weather data from the National Climatic Data Center weather data for the Randolph Air Force Base for the dates from October 1\textsuperscript{st}, 1997 through February 28\textsuperscript{th}, 1998 for use in calibrating and verifying the water quality model data set. USFWS stowaway temperature logger data had been gathered from nine separate locations within the San Marcos River system (Figure 7) for the same purpose and data sets ran from September 5\textsuperscript{th}, 1997 through September 29\textsuperscript{th}, 1998. The two hottest two day periods for which suitable NOAA and USFWS data existed were then chosen for use in QUAL2EU calibration and verification modeling. It was desired to run the model at worst case or near-worst case conditions in the system. These were

![Figure 9. QUAL2EU Water Temperature Calibration Results at City Park Temperature Logging Station.](image)

QUAL2EU water temperature calibration results at the City Park temperature logging
station. QUAL2EU results are the bold line, observed data are the thin line.

Figure 10. QUAL2EU Water Temperature Verification Results at City Park Temperature Logging Station.

identified as hot summer days with corresponding low San Marcos Springs flows and high state fish hatchery and City of San Marcos wastewater treatment plant input flows. The days chosen for calibration (for model runs and analysis, the calibration weather set was re-used) and verification were September 8\textsuperscript{th} and 9\textsuperscript{th}, 1997 and October 1\textsuperscript{st} and 2\textsuperscript{nd}, 1997.
The QUAL2EU model was run in a dynamic rather than static temperature modeling mode in order to obtain the maximum water temperatures for each day. Using the static mode would only give the daily mean temperature, a value which can lead one to believe habitat is thermally suitable when, in fact, daily temperature swings may be much greater. The maximum daily temperature in each section was the temperature used in habitat analysis.

In order to achieve a representative 24 hour temperature range, the model was calibrated, verified, and run for 48 hours with the second 24 hour period being used for temperature analysis while the first 24 hour period was used as a model spin-up period only and was not considered for actual habitat analysis. Model calibration and verification runs were re-run until modeled data matched observed data to within 2°F (Figures 8 and 9). Desired flows were then entered into the data set with San Marcos Springs and Sink Creek flows adjusted accordingly. A.E. Wood State Fish Hatchery and City of San Marcos wastewater treatment plant flows were held constant at their maximum levels of 5 MGD (75°F) and 9 MGD (78°F) respectively.

After model runs were made at total San Marcos flows ranging from 15 to 170 cfs, a spreadsheet macro was run on the data to produce water temperature tables that could be easily imported into ArcView for GIS analysis.

Habitat Modeling Approach

Flow Inputs

In order to best simulate actual system flows, several inputs other than San Marcos Springs water were incorporated into the model.

INSE/USFWS field discharge measurements in the summer of 1997 showed Sink Creek flowrate to be extremely small at 1.8 cfs (October 1, 1997). For the 2-D hydraulic model, up to five cfs was added in the entire slough area at medium to high modeled flows in order to simulate discharge and golf course runoff through this area.

With up to two hundred individual San Marcos Springs in Spring Lake (Brune, 1981), modeling springs input in the lake was a challenge. A map of the eighteen largest springs in Spring Lake oriented to North American Datum (NAD) 83 coordinates to match the system GIS coordinate system was obtained from the USFWS. This data was then overlaid on the 2-D hydraulic mesh and at each hydraulic cell containing a spring, a source input was created in the hydraulic model. Total modeled San Marcos Springs flow was divided by twenty-one (eighteen largest springs with three springs at double the flow) and the resulting discharge assigned to each spring (plus double the flow for the three largest springs). This data was then transferred to the 1-D water quality model to best represent springs input.

A.E. Wood State Fish Hatchery has applied to the Texas Natural Resource Conservation Commission for a 5 MGD effluent discharge permit. A standard wastewater treatment discharge curve was taken from Tchobanoglous (1991) and scaled up to match this 5 MGD rate. The maximum discharge during the day was 23.2 cfs, and this flow was added to the 2-D hydraulic model and QUAL2EU water temperature model at the appropriate location at all modeled flows. Hydraulic and water quality sections downstream also carried this flow. Outflow temperature was matched to field data recorded by USFWS stowaway temperature loggers during the

The City of San Marcos wastewater treatment plant is in the process of upgrading to a 9 MGD discharge. A standard daily wastewater discharge curve was scaled to 9 MGD and the maximum instantaneous discharge (41.8 cfs) was taken from this curve and applied to the 2-D hydraulic and 1-D water quality models at the appropriate location at all modeled discharges.

GIS Analysis

In order to utilize GIS in the analysis stage of this project, FESWMS 2-D hydraulic data sets and solution files had to be imported into ArcView. A custom C++ program was written to perform this conversion. Once the FESWMS hydraulic reaches and elements were saved in the ArcView format, they could be analyzed using spatial and database-based analyses only available in GIS.

DISCUSSION

System-Wide Fountain Darter Weighted Usable Area

Table 7. Modeled fountain darter weighted usable area by total San Marcos Springs flow

<table>
<thead>
<tr>
<th>Total San Marcos Springs Flow</th>
<th>15 cfs</th>
<th>30 cfs</th>
<th>65 cfs</th>
<th>100 cfs</th>
<th>135 cfs</th>
<th>170 cfs</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>WUA (ft²)</td>
<td>WUA (ft²)</td>
<td>WUA (ft²)</td>
<td>WUA (ft²)</td>
<td>WUA (ft²)</td>
<td>WUA (ft²)</td>
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<td>263163</td>
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<td>46335</td>
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<td>464245</td>
<td>601026</td>
<td>667530</td>
<td>698851</td>
<td>693565</td>
</tr>
</tbody>
</table>

Spring Lake

GIS analysis of the fountain darter WUA results revealed that the Spring Lake slough area had poor fountain darter WUA values at all modeled flows. Depths and velocities were in suitable ranges for the fountain darter for these flows but mean water temperatures were very high at all flows due to lack of flow coming down the Sink Creek channel through the slough. The average water temperature was always at the upper limit of usable temperatures for the fountain darter, and at a temperature which may impact fountain darter breeding. Field observations have shown the slough to become a vegetation-choked backwater area with extremely low flow and elevated temperatures, confirming the modeling result. Note that the slough area is only wetted due to the Spring Lake Dam backwater and does not contain any major springs. Fountain darter sampling (n = 31)in the slough (section 2) pooled across all five rounds provided an estimate of fountain darter density of 4.39 individuals per meter². One slough sample found 51 fountain darters in the 2.0 meter² enclosed by the drop net.
The non-slough area of Spring Lake showed slightly decreasing fountain darter WUA as flows decreased. Water depths remained fairly constant due to the Spring Lake Dam backwater and had little effect on fountain darter WUA. Water velocities were extremely slow at all modeled flows due to the backwater effect and were not a limiting factor. Water temperatures increased as flows decreased and this was the limiting habitat factor at the lower flows. The lowest part of Spring Lake receives the combined flows of the springs area and the slough and was more prone to rising temperatures.

Overall Spring Lake fountain darter WUA showed a consistent decrease as flows decreased. The lack of fountain darter WUA in the slough area in the modeled summer scenario combined with the size of the slough (one half of total Spring Lake area) acted as a buffer on Spring Lake WUA values (Table 7).

**Rio Vista**

Habitat modeling showed consistently increasing fountain darter WUA with increasing flows. The WUA for 135 cfs and 170 cfs modeled total San Marcos Springs flows (tSMSf) were about the same. This could be interpreted as either a peak value or as an inflection point but habitat model runs at flows higher than 170 cfs would be required to make this determination.

Rio Vista and Mill Race habitat sections were the sections in the San Marcos River system with the highest vegetation coverages according to the USACE vegetation map although Rio Vista section had much more vegetative diversity than the Mill Race section. This was of overall benefit to the fountain darter as areas with little vegetation had low HSI values for fountain darters (Table 7).

Water temperatures increased as modeled flows decreased and were of moderate importance as a habitat-limiting factor. Mean water depths in the Rio Vista habitat section fell below the two ft threshold between 30 cfs and 65 cfs and began to limit fountain darter WUA. Mean water velocities in this section never rose above the 0.5 ft/s threshold at which they would have become habitat-limiting.

Overall fountain darter WUA was limited by depths and temperatures at low flows for the Rio Vista Dam habitat section. Depths could be increased by adding planks to the Rio Vista Dam notch at very low flows (< 65 cfs) but this would exacerbate elevated water temperature effects due to increased retention times.

**Above Cape’s**

The Above Cape’s habitat modeling section starts immediately below Rio Vista Dam and stretches downstream to Cape’s Dam. Habitat at the upper boundary is characterized by fast, shallow water while habitat further downstream is dominated by Cape’s Dam backwater and has low velocity and greater depths (up to 17 ft just upstream of Cape’s Dam). This lower section exhibited a diverse range of vegetation species but was dominated by hydrilla in-channel and taro on channel banks near Cape’s Dam.

The vegetation mix in this section was generally beneficial for fountain darter WUA with the area dominated by hydrilla being particular suitable (Table 6). Mean water depths in this
section were 3.46 feet at the lowest flow modeled and increased as flows increased, never becoming habitat limiting for fountain darters.

Water temperatures increased at lower flows and became habitat limiting at modeled flows of 65 cfs and below. This effect was offset by velocities which increased over the 0.5 ft/s habitat limiting threshold between 100 and 135 cfs and began to limit habitat. The combined effect was that fountain darter WUA formed a peak at the 100 cfs modeled flow and fell on both sides of this peak (Table 7).

**Mill Race**

The Mill Race and Rio Vista habitat sections had the densest vegetation coverages according to the USACE vegetation map. The mill race in particular was dominated by hydrilla, a plant that is favorable to fountain darter presence (Table 6). The dominance of hydrilla in the mill race area led to high fountain darter WUA when temperatures and velocities were not limiting (Table 7).

As flows decreased, fountain darter WUA decreased in the Mill Race habitat section. Mean water velocity in this section never exceeded the 0.5 ft/s threshold at which it would have become limiting. Mean water depth did decrease to 3.4 ft at 15 cfs from 4.9 ft at 170 cfs. Both depths are sufficient for fountain darter WUA requirements however and depth did not prove to be a limiting habitat variable. Depths through this section did not vary much due to the mill race outfall backwater. The mill race outfall is a multi-notched weir and allows only moderate changes in water surface elevations with falling flows.

Water temperatures increased in the Mill Race habitat section and were the limiting factor for fountain darter habitat at flows below 65 cfs. The only way this could be rectified is by changing the backwater effects and retention times of Cape’s Dam, Rio Vista Dam and Spring Lake Dams upstream of the mill race. Any change in these backwater effects would also impact wild-rice however, and that effect would need to be quantified.

**State Hatchery A**

State Hatchery A habitat segment started on the main channel of the San Marcos River just below Cape’s Dam and runs 0.45 miles downstream with the last 0.1 mile of the section characterized by fast, shallow water in rapid conditions. The section is sparsely vegetated with one large patch of hydrilla being the distinguishing feature. This lack of vegetation in this area limits fountain darter WUA values.

Water temperatures rose as flows decreased especially below 100 cfs in the State Hatchery A segment, reducing fountain darter WUA. The increased temperatures were affected by increased retention times at Cape’s Dam, Rio Vista Dam and Spring Lake Dam upstream. Mean water depth at the 15 cfs modeled was 2.2 ft and rose as flows increased. Depth was therefore not a limiting fountain darter habitat factor.

As flow increased past 30 cfs, mean water velocities in this section rose past the 0.5 ft/s fountain darter HSI threshold and began to become habitat limiting. At the highest flow modeled (170 cfs), fountain darter WUA actually dropped due to this effect. Overall, lack of vegetation and elevated water temperatures at flows less than 65 cfs minimized fountain darter WUA in the State Hatchery A habitat section (Table 7). Water velocities also became a limiting factor above 30 cfs.
State Hatchery B  State Hatchery B habitat section was composed of the main channel of the river from County Road Bridge downstream to the confluence at the mill race outfall. This section receives the A.E. Wood State Fish Hatchery discharge about 300 feet upstream from its lower boundary. This section is of moderately high gradient and characterized by shallow, fast flowing water.

Vegetation coverage throughout was sparse and comprised mainly of taro and hydrilla species. Fountain darter WUA in this section was limited by this lack of aquatic vegetation (only 457 habitat cells of 4995 total habitat cells, or 9%, had vegetation of any sort according to USACE vegetation mapping data), and the resulting WUA value magnitudes were low (minimum 1323 ft², maximum 3702 ft²).

Mean water depths at the lowest two modeled flows were below the two foot lower threshold at which they would begin to moderately limit fountain darter habitat. Mean water velocity was only below the 0.5 ft/s threshold at which it begins to limit fountain darter habitat at the lowest two modeled flows however. Water temperatures rose with decreasing flows for this section and were also habitat limiting.

State Hatchery B habitat section was limited for all four modeled habitat variables. Increased water temperatures and decreased depths particularly below 65 cfs limited fountain darter WUA at lower modeled flows, increased water velocities limited fountain darter WUA at higher modeled flows and lack of vegetation limited fountain darter WUA at all flows (Table 7). This section of river has one of the steepest gradients left in the San Marcos River and this was likely responsible for the lack of vegetation, depth and increased velocities in this area.

Lower San Marcos A
The Lower San Marcos A segment showed no clear pattern in fountain darter WUA. The adverse effects of elevated water temperatures at lower flows were balanced by the adverse effects of increased velocities at higher flows with 100 cfs the modeled breakpoint between the effects. Mean water depths in this section were sufficiently deep (4.3 ft at the lowest modeled flow) at all flows and were not habitat limiting.

This river section had very sparse vegetation coverage according to the USACE vegetation maps, limiting fountain darter WUA. Areas with no vegetation have minimal fountain darter habitat value. Overall fountain darter WUA was limited by both temperatures and lack of vegetation. Increasing vegetation would have the greatest positive effect on fountain darter WUA.

Lower San Marcos B
The Lower San Marcos B habitat section had the lowest vegetation density of any San Marcos habitat modeling section. Only 0.8% of habitat cells (51 of 7551 total) had vegetation according to the USACE vegetation mapping. Areas devoid of vegetation make poor fountain darter habitat (Table 6) and will have lower resulting WUA’s.

Mean water depths through this area were the deepest in the San Marcos River due to the backwater from Cumming’s Dam. Deeper water per se is suitable, if not more beneficial, for fountain darters, and fountain darter habitat benefited from the Cumming’s Dam backwater. There are negative impacts to macrophytes and there to fountain darters in this section due to the
water depths and turbidity. Velocities were low throughout this section due to the backwater, also beneficial to fountain darter WUA. In summary, physical habitat for fountain darters is not the problem. Physical habitat for macrophytes is a problem in this section. This and other factors explain low fountain darter densities for this section.

Lower San Marcos B water temperatures had lower diel temperature fluctuation amplitudes than upper San Marcos River reaches. This result is thought to be due to the deepness of the river in this section which acts as a damper on the day-and-night temperature range. Temperatures fluctuated around 3°F at all flows in this section as opposed to up to 8°F in the Rio Vista habitat section at lower flows. Mean temperature did rise slightly at lower flows however, limiting fountain darter habitat to some extent.

The limiting habitat factor for fountain darters in the Lower San Marcos B section was lack of vegetation. Fountain darter WUA increased slightly at higher flows (Table 7) due mainly to lowered temperature effects.

### System-Wide Wild-rice Weighted Usable Area

Table 8. Modeled wild-rice weighted usable area by total San Marcos Spring flow.

<table>
<thead>
<tr>
<th>Total San Marcos Springs Flow</th>
<th>15 cfs WUA (ft²)</th>
<th>30 cfs WUA (ft²)</th>
<th>65 cfs WUA (ft²)</th>
<th>100 cfs WUA (ft²)</th>
<th>135 cfs WUA (ft²)</th>
<th>170 cfs WUA (ft²)</th>
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</thead>
<tbody>
<tr>
<td>15 cfs</td>
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<td>5885</td>
<td>31641</td>
<td>73213</td>
<td>127652</td>
<td>154525</td>
</tr>
<tr>
<td>Rio Vista</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Above Cape's Dam</td>
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<td></td>
<td></td>
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<tr>
<td>State Hatchery A</td>
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<td>State Hatchery B</td>
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<tr>
<td>Mill Race</td>
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<tr>
<td>Lower San Marcos A</td>
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<td></td>
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<tr>
<td>Lower San Marcos B</td>
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</tr>
</tbody>
</table>

Using Texas Parks and Wildlife wild-rice monitoring data from 1989-1992 (USFWS 1996), potential habitat area modeled was compared to records of amounts of occupied habitat. For each segment delineated above the maximum coverage recorded per segment (in any year) was summed across segments. Minimum coverages were also summed. The sum of the maximum areal coverage recorded for all segments outlined above is approximately 17,784 ft². The sum of the minimum coverage recorded for all segment outlined above is 10,822 ft². Based on the habitat suitability parameters examined, preliminary analysis show the system overall appears to have about four times more potentially suitable habitat than habitat recently occupied at 100 cfs, and over seven times more identified potential habitat than occupied habitat at 135 cfs. Similar evaluations of amounts of apparently suitable habitat and recently occupied habitat are given for individual segments below.

Potential habitat analysis may provide some indication that the system can support considerably more wild-rice, and that there is sufficient habitat for the restoration and recovery of wild-rice,
and should be a useful recovery planning tool. However, the present analysis presents only a preliminary examination of overall habitat characteristics by segment. The preliminary, often qualitative information used to determine habitat suitability curves may introduce error, and results must be used conservatively in guiding management decisions. The next phase of modeling and analytical work will examine potentially suitable habitat in a more spatially explicit manner, examining the location and relative stability of specific potential habitat sites at different flows. For immediate species management an assessment of the degree of vulnerability to low flows of sites with existing stands of wild-rice is needed. For recovery planning a more explicit assessment of the vulnerability of potential restoration sites to loss of habitat suitability in low flows would be helpful. As more information about the habitat needs and tolerances of Texas wild-rice becomes available, refinement of the habitat suitability curves would also provide greater confidence.

Spring Lake
Spring Lake did not contain any wild-rice WUA at any of the modeled flows with the exception of the 170 cfs tSMSf (Table 8). There were exactly two habitat cells located adjacent to Joe’s Crab Shack outfall that were suitable for wild-rice (and occupied), and the total area of these two cells in relation to the 4870 total habitat cells in Spring Lake is negligible. GIS analysis of Spring Lake habitat cells’ depths and velocities revealed that an ample amount of area existed with suitable depths for wild-rice. The velocity in each of these cells was below the 0.87 ft/s threshold used in the wild-rice habitat suitability curve however, limiting habitat with the exception of the two afore-mentioned cells. USACE vegetation mapping shows several stands of wild-rice immediately adjacent to the two Spring Lake outfalls. It is no coincidence that these areas are the only areas in Spring Lake with appreciable water velocities.

While Spring Lake Dam has greatly increased the wetted area of the San Marcos Springs headwater area and provided more areas with suitable depths for wild-rice, it has decreased velocities in all areas of Spring Lake to the point that negligible or no habitat existed in Spring Lake at all of the modeled flows. Spring Lake wild-rice distribution has changed from “growth .. so luxuriant that the irrigation company has trouble keeping the artificial lake .. clean” (Silveus 1933) to a few scattered stands at Joe’s Crab Shack and the east outfalls of the lake where water velocities increase. The reasons for this reported change are unknown. Water levels have probably not changed in Spring Lake over this time period. Dredging may possibly have increased water depths and decreased velocities in some areas of the lake, and changing springflows during the active growing season due to groundwater pumping may be a factor.

Rio Vista
The Rio Vista habitat section showed consistent wild-rice WUA increases with increasing flow (Table 8). Depths decreased as flows dropped but never became habitat limiting. At the lowest modeled flow (15 cfs), mean depth was 1.22 ft, just above the lower wild-rice threshold HSI value of 1.21 feet. At modeled flows of 170 cfs mean depth had increased to 3.1 ft.

Velocities were the limiting habitat factor in the Rio Vista habitat section. Mean water velocities never reached the lower wild-rice HSI velocity threshold. Wild-rice occurs at several
individual sites in the section, and the greatest current coverage for Texas wild-rice occurs here. This may indicate a slightly lower limit for minimum velocities than was initially indicated, and supports the need for refinement of the habitat suitability factors for Texas wild-rice. GIS analysis of modeled wild-rice habitat results showed habitat to be concentrated in the area of the University Drive bridge at all flows, consistent with USU field observations in 1998. The backwater effect of Rio Vista Dam results in lower water velocities, translating to diminished wild-rice habitat near the dam.

Above Rio Vista Dam the maximum cover of Texas wild-rice recorded from 1989-1992 was about 12,688 ft². The minimum areal extent recorded was about 4,642 ft². Examining the occupied habitat figures indicates that in terms of the preliminary analysis of suitable habitat, this segment (which currently contains the largest amount of Texas wild-rice) does appear to suffer a loss of suitable habitat at 100 cfs. Further, potential habitat is substantially occupied at 135 cfs.

Above Cape’s

The Above Cape’s habitat modeling section began immediately below Rio Vista Dam and continued downstream to Cape’s Dam. This section begins as a rapid/riffle habitat and changes over to a pool/slow moving water habitat as one gets closer to the dam due to Cape’s Dam backwater. Mean water depths rose from 3.46 feet to 3.8 feet as modeled tSMSfs (total flows) rose from 15 cfs to 170 cfs and were not habitat limiting with the notable exception of several deep pools above Cape’s Dam.

Mean water velocities never rose above the minimum wild-rice habitat threshold at which they would have ceased being habitat limiting. A preliminary analysis showed this segment had significantly larger areas of potentially suitable habitat than any other segment from flows of 65 cfs through flows up to 170 cfs, even though it represents only 9% of the system. About 25% of the total current wild-rice in the San Marcos River is in the section (Jackie Poole, TPWD, pers. comm, Jan 2000).

The upper part of Above Cape’s Dam section is shallow and fast but the Cape’s Dam backwater exerts hydraulic control, deepening the channel and slowing velocities about four tenths of the way through this section. Even with this effect, there is still suitable habitat very close to the dam. Wild-rice WUA rose consistently with increased flows (Table 8).

This segment (Above Cape’s) is significant to the conservation and recovery of Texas wild-rice. The maximum cover of rice recorded in this segment is approximately 6,023 ft² and the minimum cover recorded is 3,449 ft². Based on occupied habitat figures, it appears that at 100 cfs approximately four times more potentially suitable habitat exists in the segment than is occupied, and at 135 cfs approximately seven times more potentially suitable habitat than occupied habitat was identified. Based on this preliminary analysis, restoration and recovery potential in this segment appeared very good. Again, more spatially explicit analysis of the location and stability of suitable habitat (to be undertaken in the next phase of work) would be helpful, as it has been documented that currently in low flow situations stands of existing wild-rice in this segment have been adversely impacted. Further, the recent failure/breaching of Cape’s Dam presented a significant threat to Texas wild-rice, which was averted with a temporary patch. Future control of water depth/velocities in this segment of the river (either at
Cape’s Dam or at some upstream location) needs to consider the varied impacts to Texas wild-rice.

**Mill Race**

**Mill Race**

For the Mill Race habitat section, mean water depths increased from 3.45 feet to 4.9 feet as $t_{SMSf}$ increased from 15 cfs to 170 cfs. At the highest modeled flow, depths were just starting to be a limiting factor. For the rest of the flows modeled, mean water depths were within the optimal range for wild-rice and were not a limiting habitat factor.

Mean water velocities in the mill race never became high enough to be suitable for wild-rice habitat at the modeled flows. The backwater effect of the mill race outfall had a positive effect on depths for wild-rice but slowed water velocities to the point that no wild-rice habitat existed in the mill race at any of the modeled flows (Table 8). The mill-race has never been documented to support Texas wild-rice.

**State Hatchery A**

Wild-rice WUA consistently rose with increasing flows in the State Hatchery A habitat section (Table 8). Mean water depths were sufficient at all modeled flows. However, mean water velocities were not.

Mean water velocities were below the 0.87 ft/s wild-rice habitat threshold at modeled $t_{SMSf}$ flows up through 135 cfs and were the limiting habitat factor in the State Hatchery A section for wild-rice. Velocities showed a consistent increase as flow increased.

State Hatchery A habitat segment is probably the most natural area left in the upper San Marcos River bearing in mind that one third of the total river flow is diverted away from this section in the mill race. While the State Hatchery A section begins just below Cape’s Dam, water surface elevations are not controlled by a downstream dam and the river is allowed to flow naturally through this section. It is interesting to note that at flows near the historic mean (135 cfs and 170 cfs modeled versus 148 cfs for the historic mean), mean water velocities were 0.87 ft/s and 0.95 ft/s, at the lower envelope of wild-rice suitability but still faster than those found anywhere in the river in the backwater area of any dam. Mean water depths were 3.5 ft and 3.7 ft at these modeled flows, notably in the middle of the wild-rice optimal depth envelope. UNT researchers have not found wild-rice in this section during recent surveys.

According to this preliminary analysis, habitat availability in this segment is approaching twice the amount of suitable habitat found in the above Rio Vista segment (where the greatest cover of Texas wild-rice is generally found). Maximum cover of rice recorded in this section since 1989 was only 266 ft². The presence of unoccupied yet apparently suitable habitat for the species and the decline and loss of rice in the segment suggests that and other factors may be involved in determining why the species occurs at certain specific sites and not at others that appear to be very similar. Careful, comprehensive habitat evaluation is necessary in making conservation decisions and recovery planning.
State Hatchery B

State Hatchery B habitat modeling showed an consistent wild-rice WUA gain for increasing flows (Table 8). Mean water depths ranged from 1.8 feet to 2.6 feet at modeled tSMSfs flows of 15 and 170 cfs respectively with all values being suitable for wild-rice habitat and never becoming habitat limiting.

Mean water velocity increased past the lower wild-rice threshold of 0.87 ft/s somewhere between the 100 cfs and 135 cfs modeled flows. At the 100 cfs modeled flow and below, mean water velocity was a limiting habitat factor. WUA decreased by 73% between 100 cfs and 65 cfs.

Maximum recorded occupied habitat in this segment was about 1297 ft$^2$ and minimum recorded cover was 398 ft$^2$. Preliminary analysis indicates good recovery potential, with over 14,000 ft$^2$ of potentially suitable habitat at 100 cfs, and 29,714 ft$^2$ of potentially suitable habitat at historic mean flows of 135 cfs.

Lower San Marcos A

The Lower San Marcos A habitat segment begins at the mill race outfall, continues past the confluence with the main San Marcos River channel and the City of San Marcos wastewater treatment plant input and ends 0.8 miles downstream of the mill race/main channel confluence. This section is a transition area from the shallower upstream reaches to the deeper Cumming’s Dam backwaters found downstream and contains habitat of both types. Two glides/runs with higher water velocities exist in this section, one about 0.1 miles below the mill race/main channel confluence and the second at the wastewater treatment plant, with higher velocities that become more noticeable as flows dropped. At the higher flows modeled, the velocities in these sections of river were similar to those found throughout the section.

At the lower modeled flows, the mean velocity in this section was below the 0.87 ft/s threshold suitable to wild-rice. The 170 cfs flow had over seven time as much wild-rice WUA as the 15 cfs flow. Lower San Marcos A habitat section wild-rice WUA consistently increased with increasing flow (Table 8). The limiting habitat factor for the Lower San Marcos A habitat section was water velocity. Only at the highest modeled flow were water depths beginning to limit wild-rice WUA.

Maximum recorded areal extent for Texas wild-rice in this segment was about 2,212 ft$^2$ and the minimum recorded was about 840 ft$^2$. Based on preliminary analysis showing 5,617 ft$^2$ of potentially suitable habitat at 100 cfs and 7021 ft$^2$ of potentially suitable habitat at 135 cfs it appears there may also be significant recovery potential in this segment.

Lower San Marcos B

The Lower San Marcos B habitat segment begins about 3.1 miles below Spring Lake Dam (0.8 miles below the mill race/main channel confluence) and continues downstream to the confluence with the Blanco River. This section is the deepest and slowest moving area in the San Marcos River due to Cumming’s Dam backwater. Flow through this area is noticeably more turbid than areas further upstream and this could be due to urban or agricultural run-off, natural river processes or the combined discharges of the A.E. Wood State Hatchery and City of San
Marcos wastewater treatment plant. It is important to note that this section lies downstream of historical wild-rice distributions.

Wild-rice habitat modeling revealed that negligible wild-rice WUA existed at any of the modeled flows (Table 8). There was only one cell WUA out of 7551 total cells at 170 cfs tSMSf. Mean water depth in this section ranged from 7.7 feet to 9.3 feet at the modeled flows of 15 and 170 cfs, both values are above the upper threshold of 5.19 feet for suitable wild-rice habitat.

Selecting those cells with depths in the suitable wild-rice habitat range (513 cells of 7551 cells total at 100 cfs) and then removing cells with velocities too low for suitable wild-rice habitat left zero cells and habitat at all flows. The Lower San Marcos B section is too deep and slow moving to be considered suitable wild-rice habitat. Monitoring data showed one small patch of Texas wild-rice was recorded in the segment, though it did not persist for long. If the backwater effect from Cumming’s Dam was altered to allow for shallower depths and faster water velocities, it is possible that this area could be changed to depth/velocity parameters suitable for wild-rice, although this area is not historically wild-rice habitat. Other factors such as turbidity, water chemistry, and substrate that were not modeled here may be limiting factors.

Maximum area occupied by Texas wild-rice in this segment is about 6 ft², from a single record.

**Mill Race/Main Channel Flow Split Optimization**

Habitat modeling was employed to determine if actively partitioning of the flow split at Cape’s Dam could be used to increase fountain darter and/or wild-rice habitat in areas downstream of Cape’s Dam. To determine the answer, at each of the six system flows modeled, two mill race/main channel flow split scenarios were created. This meant splitting the total San Marcos River flow in two at Cape’s Dam and then altering how much water went down each channel. Two different flow split scenarios at each of the six system flows modeled created a grand total of twelve mill race/main channel flow split scenarios.

INSE/USFWS field measurements revealed that under historical average flow conditions approximately one-third of the total river discharge flows down the mill race with the remaining two-thirds discharge flowing over (and through) Cape’s Dam and continuing down the main channel. (INSE/USFWS measurements taken August 21st, 1998 showed 30.3% total river flow of 146 cfs going down the mill race.) The habitat model was run with one-third of the total river flow going down the mill race (leaving two-thirds down the main channel) and then with one-third total river flow going down the main channel (two-thirds down the mill race), split occurring at Cape’s Dam to quantify the optimal flow split.

Water temperature modeling revealed virtually no difference between the one-third flow split scenarios for the habitat sections downstream of the mill race/main channel confluence (sections upstream would not be affected at all). The maximum temperature change in all downstream sections (lower San Marcos habitat modeling sections A-G) was 0.27°F and was considered negligible. For these lower sections, vegetation was held constant at all flows and water depths and velocities would be unaffected by the flow split at Cape’s Dam as the split flows joined together above the lower sections. Negligible temperature change and no change in vegetation coverage, depths or velocities in these lower sections meant that they did not have to be modeled for flow split optimization purposes. Only the Mill Race, State Hatchery A and State
Hatchery B sections were modeled for flow split optimization purposes.

The partitioning of split flows used in this report may not contain the preferred flow partitioning. More simulations with lower flows down the mill race will be required to analyze the effects of the range of flow options before final management decisions could be made.

Cape’s Dam Flow Split Temperature Effects

Average temperature difference between the two flow split scenarios was 2.52°F for State Hatchery A section and 2.09°F for State Hatchery B section with mean section water temperatures lower when two-thirds total river flow was partitioned through these main channel sections. Partitioning only one-third if the total river flow through these main channel sections raised water temperature as would be expected with less flow. Similarly, the mill race exhibited increased temperatures (0.54°F averaged over all flows) at all scenarios in which only one-third total river flow was partitioned down the mill race channel. Partitioning more water (two-thirds of the total river flow) down the mill race channel lowered water temperatures in that channel as should be expected.

Cape’s Dam Flow Split Fountain Darter and Wild-rice Habitat Effects

Flow split optimization habitat modeling was performed using the same methods employed in the system-wide habitat modeling, just with different flow splits below Cape’s Dam. Vegetation, water temperature, velocity and depths were all considered. Habitat modeling results are shown below in Table 9.

Table 9. San Marcos Cape’s Dam flow split fountain darter and wild-rice habitat modeling results with optimal flows in bold for each species. Note that the mill race may only be able to handle up to 70 cfs.

<table>
<thead>
<tr>
<th>Total San Marcos Springs Flow (cfs)</th>
<th>Wild-rice</th>
<th>Fountain Darter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2/3 Q down</td>
<td>2/3 Q down</td>
</tr>
<tr>
<td></td>
<td>mill race</td>
<td>main channel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.0</td>
<td>24.0</td>
</tr>
<tr>
<td>30</td>
<td>24.0</td>
<td>804.4</td>
</tr>
<tr>
<td>65</td>
<td>804.4</td>
<td>5543.8</td>
</tr>
<tr>
<td>100</td>
<td>5543.8</td>
<td>31488.4</td>
</tr>
<tr>
<td>135</td>
<td>9153.2</td>
<td>59397.1</td>
</tr>
<tr>
<td>170</td>
<td>28047.9</td>
<td>66628.3</td>
</tr>
</tbody>
</table>

The mill race comprised 33.9% of total available habitat as defined by the sum of habitat sections Mill Race, State Hatchery A and State Hatchery B areas. Mill race habitat then had to be extremely suitable to even hope of matching the main channel area which was double its size.

San Marcos Cape’s Dam flow split fountain darter habitat modeling showed different partitions to be optimal, depending on the total river flow. At lower flows of 15 and 30 cfs total San Marcos Spring flow (tSMSf), fountain darter habitat was optimized by partitioning two-thirds of the total river flow down the mill race. Water temperatures played a small part in fountain darter habitat loss, but the real cause was identified when GIS analysis revealed that large areas of State Hatchery sections A and B were lost due to drying at these low flows.
While the partitioning model demonstrates benefits to fountain darters from purely physical habitat parameters by partitioning the majority of flow into the mill-race at low flows, this does not necessarily present a desirable management option due to the lack of macrophytes in the mill-race, and the Service is not entertaining such a partitioning as a management option solely to benefit darters during low flows, at the expense of wetted habitat in the natural channel. However, fountain darters do occur in mill-race at present. Maintaining mill-race darters as long as feasible by providing some flow would be desirable. The above scenarios were modeled to examine potential impacts to answer “what if” questions.

Wild-rice habitat results showed wild-rice habitat, characterized by medium depths, to be optimized by partitioning two-thirds of the river flow down the main channel at the two lowest flows. In other words, the wild-rice habitat modeling confirmed that drying in the main channel was a problem at very low flows and could be resolved by partitioning the maximum amount of flow down the main channel in order to increase depths (and velocities). However, wild-rice habitat does not consider the resulting effects on fountain darter habitat.

Modeling at the two highest flows (135 and 170 cfs tSMSf) showed that partitioning the majority of flow down the main channel would most benefit fountain darter habitat. The extra water in the main channel re-wetted area that had been dried out at lower flows thereby creating more fountain darter habitat. The two ‘medium’ flows modeled (65 and 100 cfs tSMSf) showed results that were influenced both by main channel wetting and drying as well as by temperature effects. Therefore, the optimal partition for these two flows does not show a clear trend.

Since mill race water surface elevations were backed up by the mill race outfall weir at all flows, decreasing velocities and limiting wild-rice habitat, wild-rice habitat modeling results showed a consistent preference to partition the majority of flow down the main channel where depths were not controlled by a weir and could revert to natural ranges.

The mill race flows about six inches from full at normal system flows, that is to say with about 55 cfs. It is quite probably that the mill race will not be able to handle more than about 70 cfs without over-topping unless the mill race outfall weir is modified. Higher flows were modeled for just such an instance and to answer what-if questions.

RESULTS

Fountain darter and wild-rice modeled habitat limiting factors are summarized in Table 10.

<table>
<thead>
<tr>
<th>Habitat Modeling Section</th>
<th>Total Area (ft²)</th>
<th>Areal Percentage of System</th>
<th>Wild-rice Low Flow Habitat Limiting Factor</th>
<th>Fountain Darter Low Flow Habitat Limiting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring Lake</td>
<td>869763</td>
<td>33.4</td>
<td>Velocity</td>
<td>Temperatures</td>
</tr>
<tr>
<td>Rio Vista</td>
<td>546110</td>
<td>21.0</td>
<td>Velocity</td>
<td>Temperatures and depths</td>
</tr>
<tr>
<td>Above Cape's Dam</td>
<td>244326</td>
<td>9.4</td>
<td>Velocity</td>
<td>Temperature, lack of vegetation</td>
</tr>
<tr>
<td>State Hatchery A</td>
<td>108270</td>
<td>4.2</td>
<td>Velocity</td>
<td>Temperature, lack of vegetation</td>
</tr>
<tr>
<td>State Hatchery B</td>
<td>48962</td>
<td>1.9</td>
<td>Velocity</td>
<td>Temperature, lack of vegetation, depth</td>
</tr>
<tr>
<td>Mill Race</td>
<td>80718</td>
<td>3.1</td>
<td>Velocity</td>
<td>Temperature</td>
</tr>
</tbody>
</table>
System-Wide Fountain Darter Habitat Modeling

Habitat modeling showed fountain darter weighted usable area decreased at lower San Marcos Springs flows. Spring Lake fountain darter habitat dominated total habitat within the San Marcos River system with due partly to the fact that Spring Lake contains one third of the total area in the system. The slough backwater area comprises one half of Spring Lake area however, and was not affected by different system flows due to the fact that there is little spring flow in the slough. Modeled weighted usable area in river sections below Spring Lake was largely influenced by elevated water temperatures at the lower flows modeled (< 135 cfs). At modeled flows above 135 cfs, several system areas began to lose fountain darter habitat due to increased water velocities (Table 8). Lack of vegetation in the lower San Marcos reaches was also habitat-limiting to the fountain darter.

System-Wide Wild-rice Habitat Modeling

Water velocities were the limiting wild-rice habitat factor in all habitat modeling sections with the exception of the Lower San Marcos B section (where depth was the habitat-limiting factor). In historic wild-rice habitat areas (uppermost 2.4 miles of the San Marcos River), Spring Lake Dam, Rio Vista Dam, Cape’s Dam and the mill race outfall weir acted in concert to create backwater areas and slow water velocities, decreasing wild-rice weighted usable area and eliminating essentially all wild-rice habitat in the mill race and Spring Lake. Poole and Bowles (1996) state that Texas wild-rice does not grow in areas immediately upstream of dams where lentic conditions are approached. INSE habitat model results showing dams creating deep, slow moving backwater areas with depths and velocities outside the range suitable for wild-rice habitat. There is substantially more habitat available than is currently occupied. There are four dams affecting the upper San Marcos River. These dams are in various states of disrepair. Dam alterations (including removal) are currently under discussion. In the case of Cummings Dam, clear benefits to both fountain darters and Texas wild-rice would be realized if the backwater effect was reduced. Other dams (e.g., Capes) have an obligate wetland plant (Texas wild-rice) established within the backwater effect of the dam sometime in the 20th century. The failure of Capes Dam could mean further losses to a dwindling endemic. Flexible engineered solutions are indicated to enable a wide range of backwater configurations.

Cape’s Dam Flow Split and Fountain Darter and Wild-rice Habitat Optimization

Wild-rice habitat modeling showed that habitat is optimized at all flows by partitioning at least two-thirds of the total river flow down the main San Marcos River channel. Fountain darter habitat was optimized by putting two thirds down the main channel at 65 cfs, 135 cfs, 170 cfs and by diverting two thirds down the mill race at 15 cfs, 30 cfs, and 100 cfs. With the two species requiring the majority two-thirds river flow down different channels a decision must be made for which species to ‘optimize’ habitat in this area. Many factors would play into this decision but one may wish to consider the fact that fountain darters are able to move in the system (to a limited degree) while the wild-rice is fixed and limited by depth and velocity.
regimes dam operators create through dam management.

**GIS Analysis**

The use of a geographic information system was extremely insightful for habitat analysis in the San Marcos River system. Each habitat cell was assigned a USACE-mapped vegetation species and INSE-modeled water velocity, depth, water surface elevation, bed elevation, hydraulic roughness, velocity-at-15 cm above channel bottom, and an inverse-distance-weighted interpolated water temperature. Aerial photos, staff gage locations, stowaway temperature logger locations, TPWD-generated edge-of-water maps with wastewater treatment plant and state hatchery discharge points were also added. The GIS allowed detailed selection criteria to be applied to each section to determine the limiting habitat factor(s), resulting in the identification of the habitat-limiting factors shown in Table 10.
REFERENCES CITED


