Evaluation of the Proposed Edwards Aquifer Recovery Implementation Program Drought of Record Minimum Flow Regimes in the Comal and San Marcos River Systems

Prepared for:

The Edwards Aquifer Recovery Implementation Program

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Executive Summary

Flow regimes within the Comal and San Marcos River systems were under consideration by the Edwards Aquifer Recovery Implementation Program (EARIP) to provide protection strategies for the aquatic resources during similar instances as the drought of record. Physical habitat for fountain darter (*Etheostoma fonticola*) and Texas wild rice (*Zizania texana*) were evaluated based on updated two-dimensional hydrodynamic models of each river system. A total of 40,456 in water topography points were collected over ~ 5.5 miles of the San Marcos River and a total of 130,065 topography points were collected over ~ 3.2 miles of the Comal River and were used to generate underlying 0.5 meter (~ 1.6 foot) computational grids used in both the hydraulic and habitat modeling of physical habitat. Habitat suitability criteria for fountain darters and Texas wild rice (TWR) were updated based on monitoring data collected over the past 8 years and input from species experts. Vegetation mapping was conducted in both river systems and integrated into the hydraulic modeling as spatially explicit roughness and in the habitat modeling as vegetation composition. Vegetation polygons were mapped to a 1.0 meter (3 foot) minimum sized and included delineation of dominant and subdominant aerial composition for mixed stands. The 2009 Texas wild rice monitoring data collected the Texas Parks and Wildlife Department and U.S. Fish and Wildlife Service were integrated with our vegetation maps. Qual2e water temperature models for both systems were recalibrated using the July 2009 meteorological data and measured water temperature data at several locations between the headwaters and downstream reaches. Overall hourly temperatures calibrations for both rivers and all locations were within 0.5 to 1.5 F.

Physical habitat simulations within the San Marcos River for TWR based on available optimal habitat areas indicated that the proposed flow regime within the San Marcos River being considered by the EARIP will provide adequate quantity and quality habitat to sustain this species during similar instances as the drought of record **provided** effective recreation control can be implemented. Analyses examining the potential benefit from removal of non-native vegetation within mixed stands of TWR in optimal areas and removal of non-natives within a 2 meter buffer of occupied optimal TWR stands can substantially increase aerial coverage of TWR. The analyses also provided information on locations of hydraulically optimal TWR locations over a range discharge that can guide adaptive management activities for increasing the distribution of TWR through plant introductions in these areas.

Fountain darter simulations based on physical habitat indicated that the flow regime being considered in the San Marcos River will provide adequate quantity and quality necessary to provide protection for this species during similar instances as the drought of record. Temperature simulations over the upper and lower limit of the proposed flow regime (i.e., 45 to 80 cfs) suggested the San Marcos River will maintain sufficient areas where water temperatures will remain below critical thermal thresholds for increased larval mortalities or viable egg production at the lower flow range and that suitable areas are both temporally and spatially extended at the higher discharge range. This supports the notion that if the lower flow range maintained at six months is followed by improved flow (and temperature) conditions at the higher flow range, and will provide adequate darter reproduction and recruitment in the event of another drought of record. Simulation results also suggest that during the peak seasonal darter reproduction period (spring) lower ambient air temperatures are expected to increase both the spatial and temporal areas suitable for darter reproduction and recruitment even at the lower range of discharges for the proposed flow regime. Due to the strong association of darters and vegetation, control of vegetation disturbance due to recreation is also critical. Protection of the aquatic vegetation extends to the EARIP proposed mitigation for non-native species control such as suckermouth catfish, tilapia, nutria, or other species that could impact the aquatic vegetation community.

Simulations of physical habitat for darters within the Comal River suggested that physical habitat will not be limiting over the flow ranges (i.e., 30 to 80 cfs) being evaluated by the EARIP. The highest quality habitat remains in the old channel and is linked to both the presence of aquatic vegetation and suitable hydraulic conditions. From a physical habitat perspective, Landa Lake also provides high quality habitat over the proposed flow regime discharge levels. Temperature simulations indicated that at the lower flow range (30 cfs), suitable darter habitat in terms of thermal requirements for reproduction and recruitment will be maintained over the upper half of the old channel. Although the Qual2e model suggested that lower Landa Lake will exceed the thermal thresholds for increased larval mortality, we believe it over estimates the thermal impacts. As noted in the results and discussion section of the report for the Comal River, we hypothesized that thermal refugia will develop along the bottom of Landa Lake due to the boundary layer development from aquatic vegetation and higher water density of the cooler spring flows compared to the hotter water from mid-Landa Lake areas. This is in part, supported by thermograph data from the Spring Island area of Landa Lake, although at higher discharge levels than those proposed by the EARIP. We believe flow regime characteristics at the higher discharge range will greatly expand suitable reproduction and recruitment areas for darter within Landa Lake and extend these areas within the old channel both spatially and temporally. As was noted for the San Marcos, the simulation results are for the hottest period in combination with the lowest flows and that during the late fall, winter and the peak reproductive period of the spring, lower ambient air temperatures result in the expansion spatially and temporally of thermally suitable darter habitat. Based on the simulation results we believe the flow ranges being considered by the EARIP for the Comal will permit sustained populations of darters (and Comal Springs riffle beetles) over a repeat of the drought of the record. Comal Springs riffle beetles main occupied spring locations at the lowest discharge (i.e., 30 cfs) and get improved conditions at the higher flow magnitudes (i.e., 60 to 80 cfs) from increased spring flow volumes and inundation of areas within the lower extant of Spring Runs 1,2, and 3.

The greatest area of uncertainty in evaluation of the proposed flow regime being considered by the EARIP in the Comal River are related to the response of the aquatic vegetation to sustained lower flows within lower Landa Lake and the potential for cool water inflows from springs along the western margin of Landa Lake 'short-circuiting' down the new channel instead of entering the old channel. These concerns are addressed in the results and discussion section of the report as well as in the recommendations for future work under the proposed adaptive management program being considered by the EARIP.

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Introduction

This report provides technical documentation on the modeling approaches and evaluation of the proposed minimum flow regime targets adopted by the Edwards Aquifer Recovery Implementation Program during a similar instance as the drought of record. It should be stressed that these flow regimes are specifically chosen to ensure short term survival of the aquatic resources within the Comal and San Marcos River systems during a similar instance of the drought of record that will ensure populations are maintained at a level that will ensure 'recovery potential' under improved flow regimes. These flow regimes cannot be sustained indefinitely (i.e., beyond the time period associated with the drought of record) without irreparable harm to the resources and/or placing these aquatic resources at unacceptable levels of risk. The assessments also explicitly assume that all the proposed mitigation measures identified and adopted by the EARIP are implemented successfully. The flow regime examined in this report is indicative of the expected flow magnitudes and their durations and has not been adopted by the EARIP.

The report details the methodologies utilized for data collection, documents the application of the various models utilized, and provides both quantitative and qualitative assessments of the flow regimes for target species in light of their habitat and life history requirements. The report concludes with a series of recommendations for future work, where uncertainties in the modeling and biological responses are critical to validate under the EARIP proposed Adaptive Environmental and Monitoring Program.

Background

The critical issue being evaluated is what flow regimes within the Comal and San Marcos Rivers need to be maintained in order to provide adequate protection of the aquatic resources during a repeat of the drought of record. This is primarily related to the expected hydrology and potential responses of the aquatic resources to the physical, chemical, and biological processes associated with these flow regimes. Historical information and various studies over the last few decades provide some key insights to the potential effects of the EARIP proposed flow regimes (Hardy et al., 1998; Bartsch 2000; Saunders et al., 2001; Hardy 2009; BioWest 2010a, b). Hardy (2009) provided both quantitative and qualitative evaluations for target species within the Comal and San Marcos River systems based primarily on historical physical habitat and water temperature modeling. The quantitative assessments focused on physical habitat and water temperature as two key elements of the aquatic environment in light of known life history requirements of three key target species: the fountain darter (*Etheostoma fonticola*), Texas wild rice (*Zizania texana*), and the Comal Springs riffle beetle (*Heterelmis comalensis*). Qualitative evaluations were also provided for other native aquatic species (Comal Springs dryopid beetle (*Stygoparnus comalensis*), Peck's cave amphipod (*Stygobromus pecki*), San Marcos Gambusia (*Gambusia georgei*), Texas blind salamanders (*Eurycea rathbuni*), San Marcos salamanders (*Eurycea nana*), Cagle's map turtle (*Graptemys caglei*)), and several non-native species (Suckermouth Catfish (*Hypostomus sp.*), Tilapia (*Tilapia sp.)*, Nutria (*Myocastor coypus*), Elephant Ears (*Colocasia esculenta*), Giant Ramshorn Snails (*Marisa cornuarietis*), Asian snail (*Melanoides tuberculata*), Gill Parasite (*Centrocestus formosanus*).

As noted above, this report focuses on the evaluation of the proposed low flow regimes within the Comal and San Marcos River systems. However, it is important to briefly review some key empirical information related to historical low flow regimes within the Comal and San Marcos River systems and known or suspected responses in the aquatic resources.

Comal River

Gage records for the Comal River over the past 80 years indicate an average daily discharge of approximately 290 cfs. However, it is known that actual spring discharge is variable year-to-year and seasonally responsive to both short and long term precipitation events as well as to both short term and long term anthropogenic effects within the Edwards Aquifer. During the drought of record, spring flows ceased for 144 consecutive days in 1956. Spring flows within the Comal River have subsequently dropped below 60 cfs for over 100 consecutive days and below 40 cfs for over 40 consecutive days during 1984. The low mean daily flow during that period was 26 cfs. Low flows have also been observed in 1989 (62 cfs), 1990 (46 cfs), and 1996 (83 cfs).

The cessation of flows in 1956 is attributed to the extirpation of darters within the Comal River, which were subsequently reestablished via introductions. The Comal Springs riffle beetle was also extirpated from the main spring runs during this period but successfully recolonized these locations when spring flows were reestablished. The mechanism of recolonization (i.e., from spring orifices on the bottom of Landa Lake or from the aquifer) remains a point of debate. Quantitative data on population levels for these aquatic resources are not available during the 1984 through 1990 period. However, it is clear that for these low flow regime periods that conditions within the Comal River were such that these species remained at viable levels sufficient to sustain these populations. This has been demonstrated through intensive habitat and population monitoring conducted by the EAA since 2001 within the Comal River that clearly shows the target aquatic resources have maintained viable populations to this date including the extended low flow period in 2009 (BioWest 2010a). What is important to note here is that the low flow regimes subsequent to cessation of flows during the drought of record (i.e., 1956) did not result in extirpation of fountain darter, Comal Springs riffle beetle, Comal Springs dryopid beetle, or Peck's Cave amphipod.

San Marcos River

The long term average daily discharge for the San Marcos River over the past 80 years is approximately 164 cfs. During the drought of record, the lowest recorded daily discharge was 46 cfs in August of 1956 which also corresponded to the lowest observed mean monthly discharge (54 cfs). The extended low flow regime of the drought of record between 1955 and 1956 resulted in mean monthly discharges between 77 cfs and 54 cfs. No quantitative data exist for the response of target aquatic resources over this extended low flow period. Intensive monitoring of Texas Wild Rice from the late 1980s to the present have shown sustained populations during all intervening low flow regimes (e.g., 2009) although negative impacts have been associated with recreation, high flow scour events and introduction of non-native species. Intensive monitoring of habitat and populations of key target aquatic resources conducted by the EAA since 2001 within the San Marcos River clearly show that the target aquatic resources have maintained viable populations to this date including the extended low flow period in 2009 (BioWest 2010b).

EARIP Drought of Record Low Flow Regimes

Figure 1 shows an example of simulated mean monthly flows within the Comal and San Marcos River systems indicative of the type of flow regime that may be expected during a repeat of the drought of record. It is understood that these flow regimes are an approximation that broadly reflect EARIP flow targets. We further note that these are likely to be refined through further simulations reflecting EARIP implementation strategies related to mitigation and flow regime management actions. Within the Comal River, low flows are set at a minimum of 30 cfs for no more than 6 consecutive months with increased pulse flows to 80 cfs for the following 6 months. Within the San Marcos River, low flows are set at a minimum of 45 cfs for no more than 6 consecutive months with pulse flows increased to 80 cfs for the following 6 months. It should be stressed that in the evaluations of these target flow regimes, it has been assumed that the indicated flow rates are mean daily flow rates. We have also assumed that these mean daily flows are expected to have a 7 to 10 percent day to day variation based on historical data and the physical reality of aquifer responses to precipitation, evaporation, weather, etc.

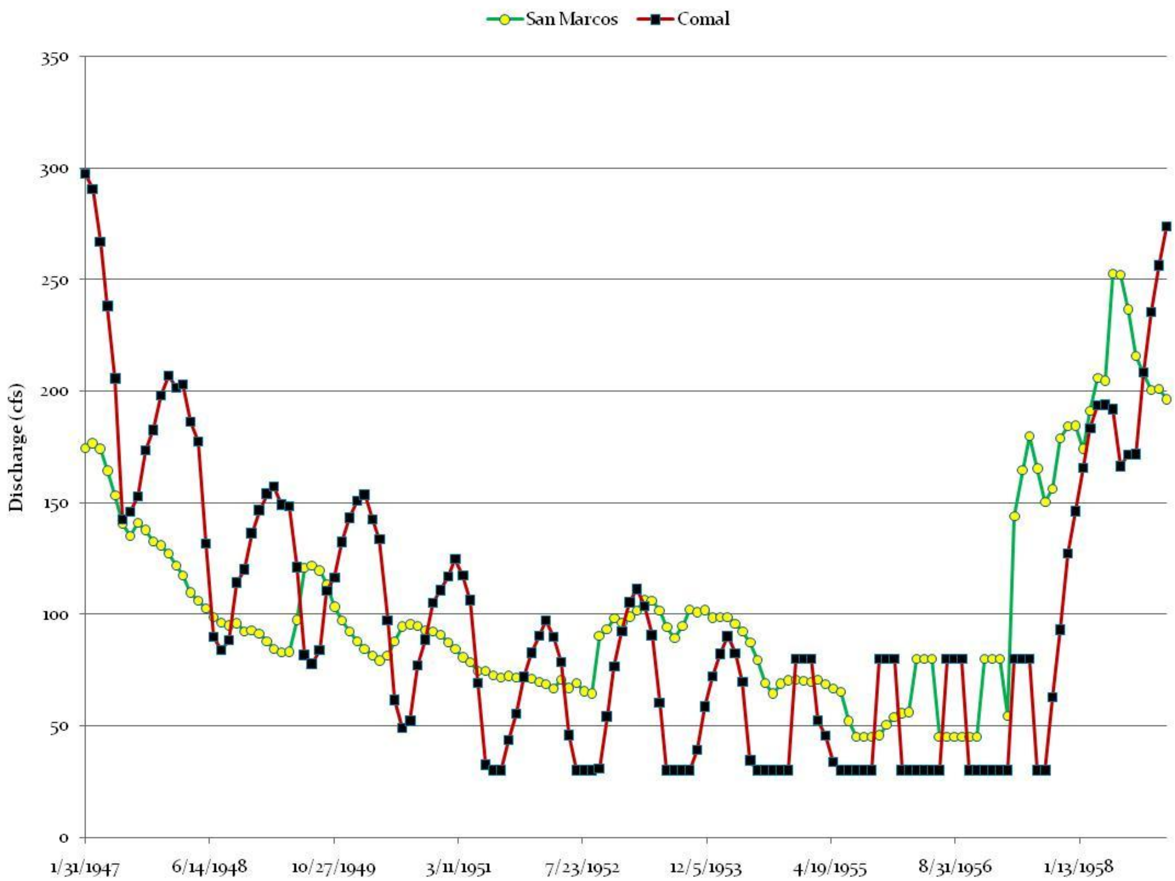


Figure 1. **An example of simulated mean monthly EARIP drought of record target flow regimes within the Comal and San Marcos River systems.**

The simulations in Figure 1 also do not reflect several key aspects of the flow regime due to the monthly time step. It is anticipated that the neither system will actually respond instantaneously to decreases or increases between the minimum and maximum low flow regime targets and that these would actually occur over the period of days or perhaps even weeks as reflected in the pre-1955 regime at Comal versus the post-1955 regime as shown. What is evident is that for these simulations the flow regime within the San Marcos River only exhibits critical low flow target minimums and pulse flows very late in the drought of record reflecting its fundamental difference in hydrogeography compared to the Comal River. This would suggest that to some degree the duration and therefore response by the aquatic community would be somewhat minimized from a strictly duration perspective. This may ‘buffer’ some of the impacts given the lag time in aquatic vegetation community responses that might be expected for longer duration events.

The simulations within the Comal River suggest target low flows will be realized much early than expressed in the San Marcos River and start as early as 1951 in this example. However, in the 1951 to 1953, the simulations suggest that the duration of the low flow minimums are of shorter duration (3 to 4 months) and those higher flows are expressed for 7 to 8 month long periods and parallel the higher flow regimes in the San Marcos River over this period. This again may provide some ‘buffer’ against impacts due to responses in the aquatic vegetation community. During the later 4 years of the drought of record it is apparent that the Comal River will operate between the minimum and maximum flow regime targets. Therefore overall habitat conditions in terms of quantity and quality for the aquatic resources need to be carefully examined for these target flow magnitudes and their durations and are the main focus of the assessments in this report.

Methods

The following section of the report provides detailed information of the quantitative aspects of the field methods, model calibrations and simulations, and species specific analytical approaches utilized to assess the target flow regimes within the Comal and San Marcos River systems from a physical habitat and water temperature perspective. For Texas Wild Rice, the strategy for assessing non-native vegetation removal is also detailed. In most cases, illustrative examples are provided to allow the reader to understand the specific approach, while comprehensive results are deferred to appendices. For example, the strategy for the hydrodynamic model calibrations is described through a single example, while all the reach specific calibration results are deferred to an appendix. In some instances, results are presented here to simplify presentation of material used in the evaluation of the flow regimes for each river.

Study Areas

Figure 2 shows the spatial extant of the assessments conducted in the Comal and San Marcos Rivers. Both Spring Lake and Landa Lake were modeled but are not indicated with polygon segments for readability in the figures. As noted in Figure 2, the assessments were not extended to the lower most reaches of the San Marcos River based on both Texas Wild Rice and Fountain darter distributions. Less than 1 percent of their distributions are located below the last modeling segment.

Field Data Collection for Channel Topography and Hydraulic Model Calibration

Topography (i.e., elevation), substrate, vegetation, and surface water elevation data for each river was collected from September 2009 – April 2010. Standard survey equipment and GPS Trimble XH units were used to measure topography within the wetted portion of the stream using a systematic irregular sampling strategy that targets capturing all available heterogeneity within the stream. Latitude (x), longitude (y), depth, and substrate type were recorded in Trimble dictionaries for each point surveyed. Vegetation within the stream was delineated with polygons with corresponding percentages of each vegetation or substrate type recorded for each polygon. Discharge and water surface elevation (WSE) longitudinal profiles were recorded each day during field measurements of channel topography. During heavy rain events, field measurements were suspended until the gage readings indicated that flows would remain relatively stable during the day to minimize changes in stage during field measurements. Measurement of the WSE longitudinal profile included delineation at any abrupt WSE change. In addition, a complete longitudinal WSE profile was measured at an additional discharge on each river.

Vegetation Mapping

Vegetation polygons were delineated using standard survey equipment and GPS Trimble XH units to define the outline of each vegetation patch of 1.0 meter or greater in area. These data were collected separately from the data set used for quantification of channel topography discussed above. For each mixed species vegetation polygon, the percent compositions of dominant and all subdominant species were noted as long as a subdominant vegetation species had more than 1.0 meter areal coverage. Existing

TPWD and USFWS vegetation surveys and TWR locations from 2009 for the San Marcos River were integrated to generate a single aquatic vegetation map for the river. Voucher specimens for all species were collected, keyed in the laboratory and used for verification of mapping results and vegetation polygon attributes. Figure 3 provides an example of the vegetation mapping results from the San Marcos River. Appendix A contains final vegetation polygons river reach for both the Comal and San Marcos River systems. Vegetation polygons were spatially joined with the hydrodynamic modeling grids to assign roughness values and vegetation class attributes for habitat modeling of darters and non-native vegetation removal assessments for TWR as noted below.

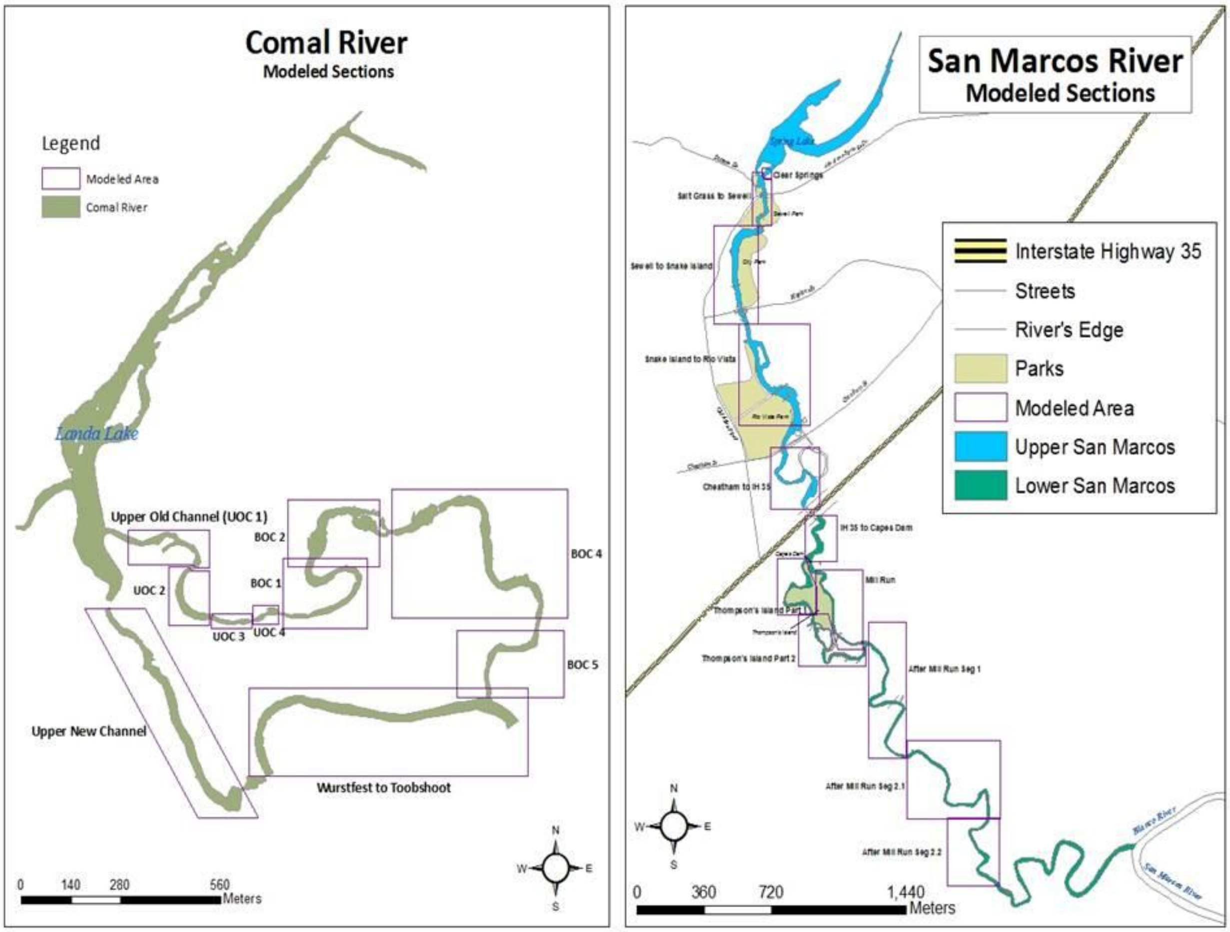


Figure 2. Comal and San Marcos River system study areas.

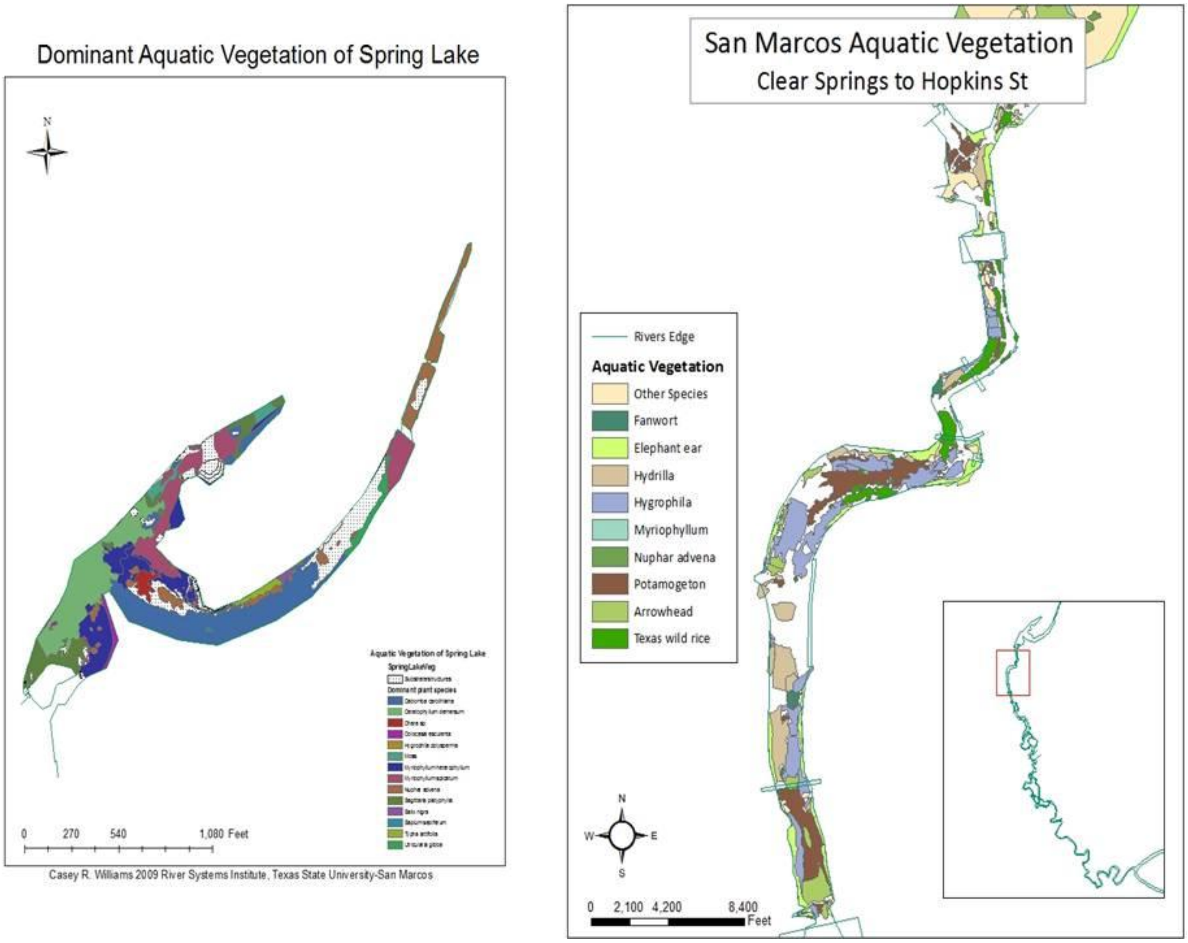


Figure 3. Example of vegetation mapping polygons from the San Marcos River.

Topographic Data Reduction and Computational Mesh Generation

Surveyed topography and vegetation data for each river were differentially corrected using GPS Pathfinder office. Contour topographic maps of Hays County, Texas were used to obtain topography data within the annual wetted channel portion of the San Marcos River and LIDAR data from the city of New Braunfels, Texas were used to obtain topography data within the annual wetted channel portion of the Comal River. These data were then merged with the in-channel bed topography data to derive a single three dimensional topography data set by river reach for each system. Topography data (i.e., x, y, bed elevation) were used to construct bathymetric maps for each river using the Multi-Dimensional Surface Water Modeling System (MDSWMS, McDonald et al. 2005). Mapping of the raw data to defined computational grids was accomplished using triangular irregular networks to derive three dimensional orthogonal rectilinear grids of approximately 0.25 meter resolution. This process is illustrated graphically in Figure 4.

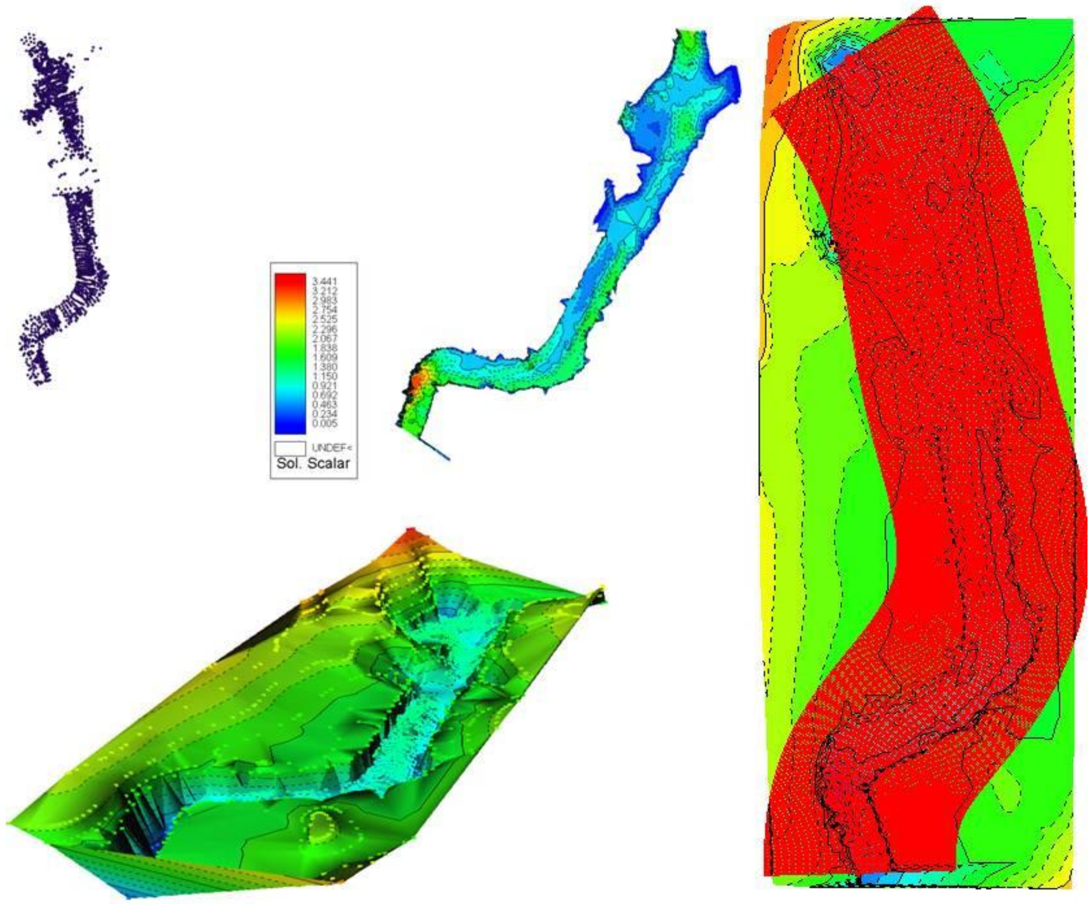


Figure 4. Example of field measured topography points, depth contours, computational mesh overlay mapped onto topography, final 3-dimensional computational grid geometry used in modeling (clockwise order).

Substrate and vegetation types were assigned specific roughness values for use in the hydrodynamic modeling as provided in Table 1. For polygons of mixed vegetation types, the area weighted average of the monotypic roughness values were computed and assigned to the grid elements falling within that mixed vegetation polygon area. Values for Table 1 were derived from published literature values and flume experiments conducted at the Utah Water Research Laboratory (Thom Hardy, personal communication). As noted previously, the vegetation polygons were also mapped to the computational grids to assign vegetation type for use in habitat modeling of darters. In this instance, the dominant vegetation class was assigned to the grid.

Hydraulic Modeling

Topography, roughness, and WSE profiles for the measured discharges were used in the Multi-Dimensional Surface Water Modeling System (MDSWMS, McDonald et al. 2005) for calibration of hydraulic models for each river segment. The San Marcos River was divided into 12 modeling segments and the Comal River was divided into 11 modeling segments based on distinct changes in river morphology and computer software limitations associated with file sizes given target grid resolutions of 0.25 meters (see Figure 1). Modeling segments of Landa Lake and Spring Lake are not delineated in Figure 1 for readability.

Table 1. Roughness (height in meters) of vegetation and substrate within the San Marcos River, Texas. Meters are reported in lieu of feet since the hydrodynamic model utilizes SI units and actual values used in modeling are reported.

Vegetation/Substrate Type	Roughness	Vegetation/Substrate Type	Roughness
Algae	0.07	Metal	0.051
Arundo donax	0.0085	Moss	0.035
Bedrock	0.051	*Myriophyllum heterophyllum*	0.055
Cabomba caroliniana	0.058	*Myriophyllum spicatum*	0.051
Ceratophyllum demursum	0.085	*Nasturtium officinale*	0.01
Ceratopteris thalictroides	0.05	*Nupahr advena*	0.09
Clay	0.000002	*Pistia stratiotes*	0.00
Cobble	0.1175	*Potamogeton illinoensis*	0.078
Colocasia esculenta	0.04	*Riccia fluitans*	0.035
Concrete	0.051	*Sagittaria platyphylla*	0.02
Eichornia crassipes	0.00	Sand	0.0032005
Gravel	0.0265	*Schoenoplectus tabernaemontani*	0.07
Heterantha dubia	0.075	Silt	0.000026
Hydrilla verticillata	0.09	Small Boulder	0.36225
Hydrocotyle sp	0.045	*Solidago sp*	0.07
Hygrophilla polysperma	0.07	Terrestrial/grass	0.07
Iris sp	0.07	*Vallisneria neotropicalis*	0.026
Justicia americana	0.035	*Vallisneria spiralis*	0.015
Large Woody Debris	1.2	Wood	1.2
Large Boulder	1.2745	*Xanthosoma sagittifolium*	0.05
Leptodictyum riparium	0.07	*Zizania texana*	0.075
Limnophila sessiliflora	0.058	*Zizaniopsis miliacea*	0.07
Ludwigia repens	0.05		

Hydraulic modeling parameters (i.e., roughness, viscosity, and relaxation parameters) for each modeled segment were adjusted until the Root Mean Square (RMS) error between observed and predicted WSE profiles was no more than 2.5 cm over the full longitudinal extant of the modeled segment and such that model solutions converged to less than 5 percent of the calibration discharge. This process was repeated for each calibration flow. Figure 5 provides an example of the RMS error evaluation used in model calibration. Appendix B contains the calibration plots for each river segment for the Comal and San Marcos Rivers. Tables 2 and 3 provide summary computational mesh characteristics and final calibration parameters for the Comal and San Marcos Rivers.

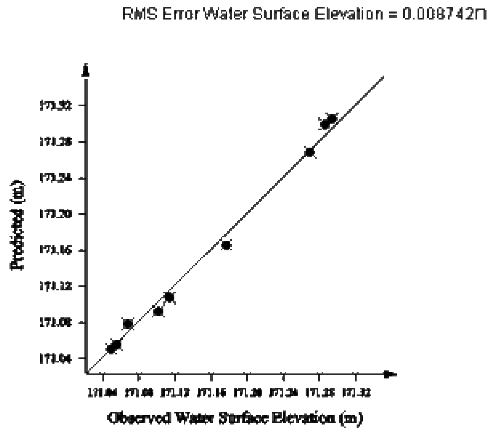


Figure 5. Example of RMS error between observed and predicted WSE profile.

Hydraulic model parameters from the two calibration discharges for each modeling segment were used to construct regressions for water surface, roughness, and viscosity as a function of discharge (Tables 4 and 5). Regressions were used to calculate hydraulic parameter values for simulated discharges used in the assessments for the Comal and San Marcos Rivers. Discharges were selected based on the range of flow targets being considered during the drought of record. MDSWMS was used to model the distribution and availability of current velocities and depths for 17 selected discharges for each modeled segment. Three dimensional solution files, comprised of a computational mess with x, y, depth, current velocity, water surface elevation, bed elevation, and cell area were exported from MDSWMS and overlaid with vegetation and substrate polygons in ArcView 9.2 to render spatially explicit maps for each modeled discharge for each river. Total stream surface area (i.e., areas with depth > 0.0 depth) within each model segment for each discharge was computed to predict total available stream area for each modeled discharge.

Habitat Suitability Criteria (HSC)

HSC for depth and velocity for TWR and two non-native aquatic vegetation species (*Hydrilla verticillata and Hygrophila polysperma)* were adapted from Saunders et al. (2001) for use in modeling physical habitat quantity and quality assessments as described below. In addition, HSC for depth, velocity, and vegetation/substrate for darters were also adapted from Saunders et al. (2001) and data provided by BioWest from field monitoring in the Comal and San Marcos between 2001 and 2009 (BioWest 2010a,b).

Figure 6 provides the depth and velocity HSC for TWR. Figure 7 and 8 provide the depth and velocity HSC for *H. verticillata* and *H. polysperma*, respectively. Figure 9 provides the HSC for depth and velocity for darters while Table 6 provides the HSC values for substrate/vegetation. The darter HSC for depth was modified to extend no limitation on depths given empirical observations while diving has shown darter utilization is the deepest parts of Landa Lake on the Comal and Spring Lake on San Marcos River. Previous curves showed declining suitability at higher depths reflective of gear bias (Thom Hardy, personal observation).

Table 2. Hydraulic calibration parameters for the 10 riverine modeling segments of the Comal River.

Comal River calibration models	Topography points	Roughness points	Grid dimensions (rows by columns)	Mean cell area (m^2)	Discharge (cms)	Roughness height (m)	Viscosity (m^2/s)	Lower SWE boundary (m)	Relaxation parameters	Iterations
Top of Old channel										
low flow	2,062	489	477 X 101	0.2517	0.85	0.0450	0.130	185.51	.4 .2 .2	10,000
high flow	2,062	489	477 X 101	0.2517	2.00	0.0500	0.130	185.59	.4 .2 .2	10,000
Upper Old Channel 2 (UOC2)										
low flow	402	402	367 X 51	0.254	0.85	0.0850	0.005	185.05	.4 .2 .2	5,000
high flow	402	402	367 X 51	0.254	1.40	0.0850	0.005	185.27	.4 .2 .2	10,000
Upper Old Channel 3 (UOC3)										
low flow	941	941	211 X 51	0.2662	0.85	0.0010	0.005	184.85	.4 .2 .2	10,000
high flow	941	941	211 X 51	0.2662	1.45	0.0010	0.005	184.95	.4 .2 .2	7,500
Upper Old Channel 4 (UOC4)										
low flow	813	813	159 X 63	0.251	0.85	0.0800	0.050	184.55	.4 .2 .2	15,000
high flow	813	813	159 X 63	0.251	1.13	0.0800	0.050	184.56	.4 .2 .2	10,000
Bottom of Old Channel (BOC1)										
low flow	6,611	6,611	921 X 71	0.2496	0.85	0.0400	0.005	183.89	.4 .2 .2	10,000
high flow	6,611	6,611	921 X 71	0.2496	1.13	0.0400	0.005	184.01	.4 .2 .2	10,000
Bottom of Old Channel 2 (BOC2)										
low flow	6,345	6,345	571 X 201	0.1872	0.85	0.0800	0.005	183.93	.4 .2 .2	10,000
high flow	6,345	6,345	571 X 201	0.1872	1.13	0.0800	0.005	183.96	.4 .2 .2	10,000
Bottom of Old Channel 4 (BOC4)										
low flow	8,084	8,084	1331 X 111	0.2532	0.85	0.0900	0.050	182.00	.4 .2 .2	10,000
high flow	8,084	8,084	1331 X 111	0.2532	1.13	0.0900	0.050	182.06	.4 .2 .2	10,000
Bottom of Old Channel 5 (BOC5)										
low flow	3,824	3,824	527 X 111	0.2532	0.85	0.0900	0.050	181.98	.4 .2 .2	1,050
high flow	3,824	3,824	527 X 111	0.2532	1.13	0.0900	0.050	182.07	.4 .2 .2	1,200
Upper New Channel										
low flow	33,562	2,314	1375 X 91	0.249	6.75	0.0100	0.070	188.79	.4 .3 .3	15,000
high flow	33,562	2,314	1375 X 91	0.249	7.20	0.0100	0.060	188.78	.4 .3 .3	15,000
Wurstfest to Toobshoot										
low flow	67,421	3,301	1781 X 201	0.2534	6.51	0.0100	0.005	181.48	.4 .3 .3	10,000
high flow	67,421	3,301	1781 X 201	0.2534	9.11	0.0100	0.005	181.69	.4 .3 .3	10,000

Table 3. Hydraulic calibration parameters for the 11 riverine modeling segments of the San Marcos River.

San Marcos River calibration models	Topography points	Roughness points	Grid dimensions (rows by columns)	Mean cell area (m^2)	Discharge (cms)	Roughness height (m)	Viscosity (m^2/s)	Lower SWE boundary (m)	Relaxation parameters	Iterations
Clear Springs										
low flow	2,181	2,117	109 X 161	0.2543	2.00	0.0015	0.030	171.65	.4 .3 .3	10,000
high flow	2,181	2,117	109 X 161	0.2543	2.80	0.0015	0.040	171.75	.4 .3 .3	5,000
Saltgrass through Sewell Park										
low flow	3,387	2,587	571 X 121	0.245	2.57	0.0290	0.010	171.05	.4 .3 .3	10,000
high flow	3,387	2,587	571 X 121	0.245	7.07	0.0420	0.010	171.56	.4 .3 .3	10,000
Sewell Park to Snake Island										
low flow	19,168	8,315	1205 X 201	0.2439	2.30	0.0600	0.030	170.77	.4 .3 . 3	10,000
high flow	19,168	8,315	1205 X 201	0.2439	7.07	0.1000	0.030	171.08	.4 .3 . 3	10,000
Snake Island to Rio Vista										
low flow	18,903	14,049	1199 X 249	0.2558	3.60	0.2000	0.005	170.52	.4 .2 .2	10,000
high flow	18,903	14,049	1199 X 249	0.2558	6.37	0.2000	0.010	170.90	.4 .2 .2	10,000
Cheatham to I35										
low flow	5,037	3,380	1175 X 129	0.2461	4.36	0.0035	0.010	168.43	.4 .3 .3	12,000
high flow	5,037	3,380	1175 X 129	0.2461	7.07	0.0064	0.010	168.58	.4 .3 .3	12,000
I35 to Capes Dam										
low flow	2,740	1,356	585 X 201	0.2319	4.47	0.0900	0.035	168.33	.4 .3 .3	10,000
high flow	2,740	1,356	585 X 201	0.2319	7.08	0.0830	0.010	168.40	.4 .3 .3	10,000
Thompson Island part 1										
low flow	3,677	1,518	1041 X 101	0.256	4.59	0.0200	0.025	166.45	.4 .3 .3	15,000
high flow	3,677	1,518	1041 X 101	0.256	6.00	0.0200	0.010	166.52	.4 .3 .3	15,000
Thompson Island part 2										
low flow	3,973	1,475	827 X 269	0.2523	4.20	0.0100	0.100	164.81	.4 .2 .2	1,050
high flow	3,973	1,475	827 X 269	0.2523	6.30	0.0100	0.100	164.98	.4 .2 .2	1,050
After Mill Run Seg 1										
low flow	5,448	2,393	1785 X 121	0.2532	4.75	0.0035	0.008	164.21	.4 .3 .3	10,000
high flow	5,448	2,393	1785 X 121	0.2532	7.07	0.0055	0.010	164.42	.4 .3 .3	10,000
After Mill Run Seg 2.1										
low flow	6,872	1,729	1551 X 91	0.2543	5.06	0.0020	0.005	164.14	.4 .3 .3	15,000
high flow	6,872	1,729	1551 X 91	0.2543	5.84	0.0020	0.005	164.33	.4 .3 .3	15,000
After Mill Run Seg 2.2										
low flow	5,233	1,537	1009 X 91	0.2534	5.06	0.0100	0.010	164.07	.4 .3 .3	20,000
high flow	5,233	1,537	1009 X 91	0.2534	5.84	0.0100	0.010	164.25	.4 .3 .3	20,000

Table 4. Regressions for calibrated hydraulic modeling parameters for 10 riverine modeling segments of the Comal River.

	Regressions		
Comal River modeling sections	Roughness height (m)	Viscosity (m2/s)	SWE (m)
Top of old channel	y = 0.0413 + 0.0043x	y = 0.13	y = 185.45 +0.0704x
UOC2	y = 0.085	y = 0.005	y = 184.72 + 0.3885x
UOC3	y = 0.001	y = 0.005	y = 184.71 + 0.1664x
UCO4	y = 0.08	y = 0.005	y = 184.51 + 0.0431x
BOC1	y = 0.04	y = 0.005	y = 183.55 + 0.409x
BOC2	y = 0.08	y = 0.005	y = 183.78 + 0.1722x
BOC4	y = 0.09	y = 0.005	y = 181.82 + 0.2119x
BOC5	y = 0.09	y = 0.05	y = 181.71 + 0.3198x
Upper new channel	y = 0.01	y = 0.22 - 0.022x	y = 188.60 + 0.0267x
Wurstfest to toobshoot	y = 0.005	y = 0.01	y = 180.95 + 0.0808x

Table 5. Regressions for calibrated hydraulic modeling parameters for 11 riverine modeling segments of the San Marcos River.

	Regressions		
San Marcos River modeling sections	Roughness height (m)	Viscosity (m^2/s)	SWE (m)
Clear Springs	y = .0015	y = 0.04	y = 171.395 + 0.1275x
Saltgrass through Sewell Park	y = 0.0216 + 0.0029x	y = 0.01	y = 170.7603 + 0.1131x
Sewell Park to Snake Island	y = 0.0407 + 0.0084x	y = 0.03	y = 170.6205 + 0.065x
Snake Island to Rio Vista	y = 0.02	y = 0.0015 + 0.0018x	y = 170.0239 + 0.1376x
Cheatham St to I35	y = -0.0012 + 0.0011x	y = 0.01	y = 168.1861 + 0.0557x
I35 to Capes	y = 0.102 - 0.0027x	y = 0.0778 - 0.0096x	y = 168.2051 + 0.0268x
Thompson Island part 1	y = 0.02	y = 0.0737 - 0.0106x	y = 166.2228 + 0.0495x
Thompson Island part 2	y = 0.01	y = 0.1	y = 164.44 + 0.0857x
After Mill Run Seg 1	y = -0.0021 + 0.0011x	y = 0.0039 + 0.0009x	y = 163.78 + 0.0905x
After Mill Run Seg 2.1	y = 0.002	y = 0.005	y = 162.9269 + 0.2397x
After Mill Run Seg 2.2	y = 0.01	y = 0.01	y = 162.9269 + 0.2269x

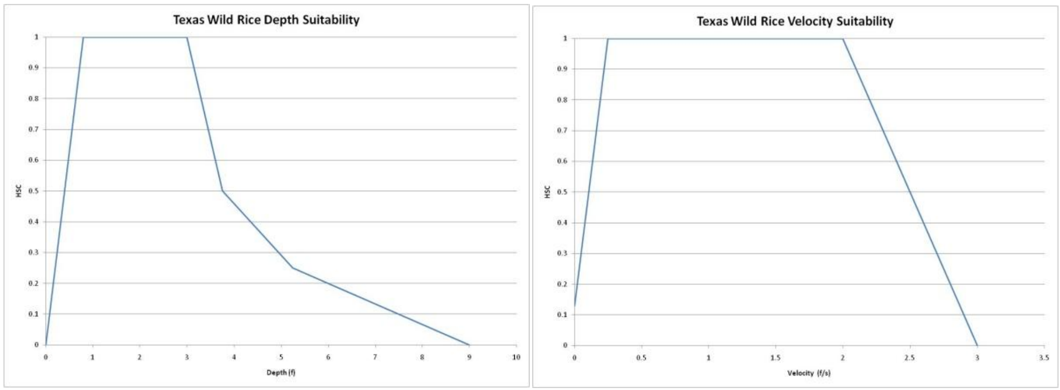


Figure 6. Depth and velocity HSC for TWR.

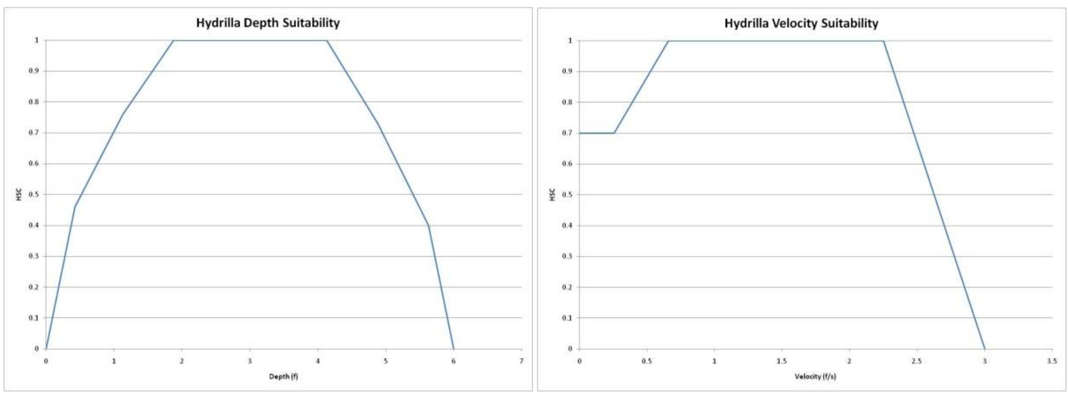


Figure 7. Depth and velocity HSC for Hydrilla.

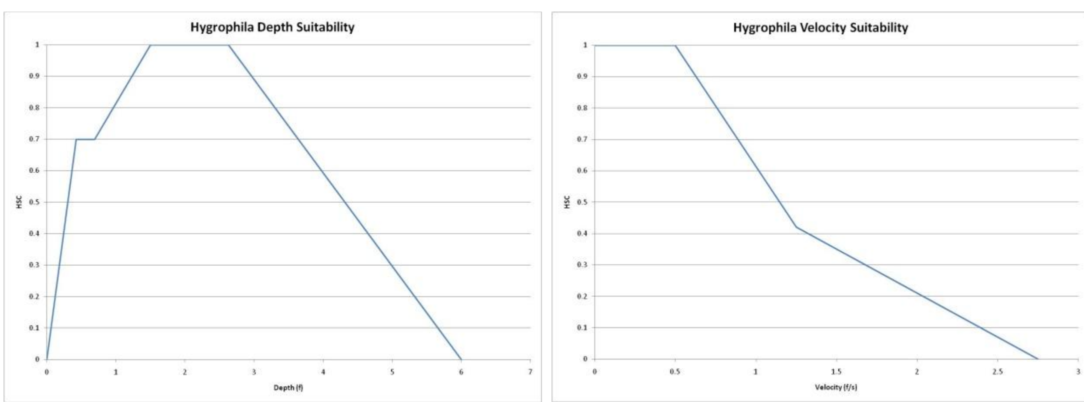


Figure 8 . Depth and velocity HSC for *Hygrophila.*

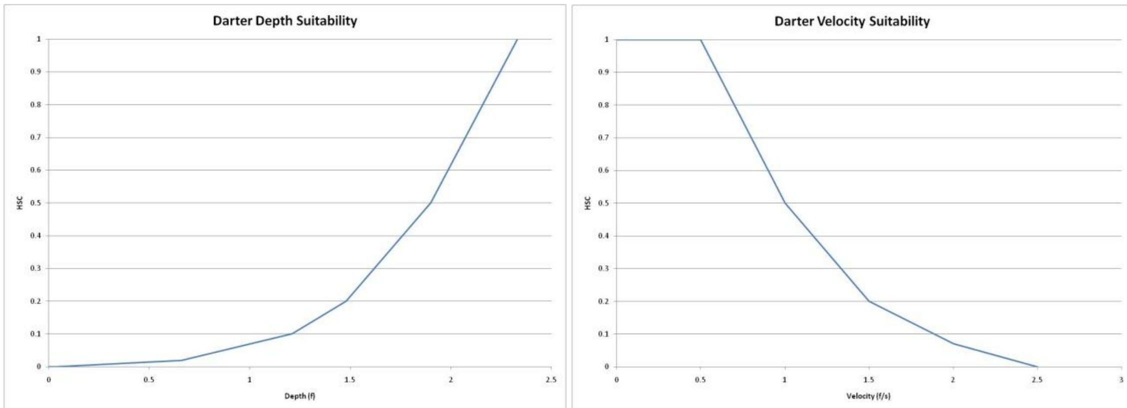


Figure 9. Depth and velocity HSC for darters.

Table 6. HSC for substrate and vegetation codes for darters.

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

Physical Habitat Quantity and Quality

Fountain Darters – Riverine Sections

Simulation results from the MDSWMS solution files were exported into Microsoft Excel and a Visual Basic for Applications utility was used to generate darter component habitat suitability index (HSI) values for depth and velocity at each computational cell based on the component HSC values for depth and current velocity. Component HSI values ranged from 0.0 to 1.0, with a value of 0.0 indicating no suitability whereas a 1.0 indicates 'optimal' conditions.

Fountain darter HSC for depth and current velocity and substrate/vegetation suitability were used to generate predicted fountain darter weighted useable area (WUA) for each modeled discharge. The combined suitability for fountain darters was derived as the geometric mean of the component suitability's for depth, velocity and substrate/vegetation as follows:

$$\text{Combined Suitability} = (\text{FDdS} * \text{FDcvS} * \text{FDsubS})^{1/3}$$

Where FDdS is the depth suitability, FDcvS is the current velocity suitability, and FDsubS is the substrate/vegetation type suitability. Basically, given the hydraulic attributes of depth and velocity at a given node location and the associated vegetation/substrate code, the component suitability for each factor are computed and the resulting geometric mean is multiplied by the area of the cell to yield WUA. The WUA for a given discharge is simply the sum of all non-zero WUA for all computational cells at that discharge. The relationship between the amount of fountain darter (WUA) upstream of Rio Vista Dam, downstream of Rio Vista dam, and the total for the San Marcos River was calculated for each modeled discharge. Similarly, results for the old channel, and the new channel were computed for the Comal River. For each system, WUA was expressed as the percent of the total surface area for each discharge.

Fountain Darters – Lake Sections

Empirical data collected by Hardy et al. (1989), Bartsch et al. (2000), and the monitoring data developed by BioWest (2010a,b) clearly show that one of the primary determinants of darter habitat utilization is association with specific vegetation types along with depth and velocities. Because the lake sections are relatively insensitive to hydraulic changes in the depth and velocity fields over the lower flow ranges being evaluated, a simplified approach was taken to estimating darter habitat for these sections of both river systems. Water surface elevations in Landa Lake in the Comal River and Spring Lake in the San Marcos River remain relatively constant over a wide range of discharges (Guyton Associates 2004) due to control structures. At Spring Lake, the vegetation mapping results and the HSC for vegetation and substrate was utilized to compute the WUA for darters as a constant over all simulated flow ranges since lake elevations over the lower flow ranges being evaluated do not materially change. The basic calculation of WUA for darters in Landa Lake based on substrate/vegetation suitability was approached in the same manner as that for Spring Lake described above. However, since areas of Landa Lake are differentially exposed at lower flow rates (see Guyton Associates 2004) the analysis relied on the stage discharge relationships developed by Bartsch et al. (2000) and the three dimensional topography of the computational grids to exclude polygon areas that were 'dry' at specific flow rates. At each flow rate of 30, 45, 50, 60, 70, and 80 cfs, the stage (water surface elevation) for that discharge was used to exclude all topography with elevations greater than that threshold. The remaining polygon areas of vegetation/substrate were then evaluated using the corresponding HSC to derive the suitability value which was then multiplied by the polygon area to generate WUA. Reduction in darter habitat areas due to thermal constraints are addressed separately in the temperature modeling described below.

Texas Wild Rice – Theoretical Optimal and Suboptimal Area

Simulation results from the MDSWMS solution files were exported into Microsoft Excel and a Visual Basic for Applications utility was used to generate TWR component habitat suitability index (HSI) values for depth and velocity at each computational cell based on the component HSC values for depth and current velocity. Component HSI values ranged from 0.0 to 1.0, with a value of 0.0 indicating no suitability whereas a 1.0 indicates 'optimal' conditions.

The HSI outputs were imported into ArcView 9.2 and converted into point and polygon shapefiles. Each point contained modeled hydraulic attributes (e.g., predicted depth and current velocity) and corresponding HSI values for depth and velocity. Point and grid polygon (i.e., computational mesh) shapefiles were joined for each modeled discharge and clipped to the river's edge. This joined point-polygon layer resembled the original modeled grid developed in MDSWMS and contained corresponding HSI values for depth and current velocity for TWR. A field was added to each modeled point-polygon attribute table to generate composite habitat suitability for depth and current velocity for TWR for each cell within the computational mesh and was calculated as the Geometric Mean of the component depth and velocity HSI.

$$\text{TWR Combined Suitability} = (\text{TWRdS} * \text{TWRcvS})^{1/2}$$

The point-polygon attribute table for each modeled discharge was exported into Microsoft Excel and the total for only 'optimal habitat' (i.e., areas with combined HSI values > 0.75 combined suitability's was calculated. It should be noted that these are predicted areas of optimal suitability and not necessarily occupied by existing TWR. Other abiotic or biotic factors such as other native or non-native vegetation may occupy these areas at present. These values conceptually represent the quantity of 'high quality' habitat that <u>theoretically</u> contains 'optimal' depth and velocity conditions for TWR.

The relationship between the amount of predicted optimum TWR areas upstream of Rio Vista Dam, downstream of Rio Vista dam, and the total San Marcos River were calculated for each modeled discharge. The San Marcos River was divided by Rio Vista dam based on the changes in river morphology upstream and downstream of the dam. WUA was also expressed as the percent of the total surface area for each discharge. Plan view plots of the combined suitability predicted for TWR for each modeled section for each flow rate were also generated. These are provided to aid the EARIP in further evaluation of the spatial component of such factors as recreation control under low flow conditions and aid in the identification of potential TWR introduction sites that would be anticipated to maintain high suitability over a range of target discharges.

Texas Wild Rice – Occupied Optimal and Suboptimal Area

A layer containing the vegetation polygons mapped in the San Marcos River during 2009 was spatially joined to the point-polygon layer for each modeled discharge. The attribute file containing joined information (i.e., combined TWR HSI values and 2009 mapped TWR polygon areas) was exported to Microsoft Excel. Predicted areas for the 2009 mapped TWR populations occurring within optimum (i.e., > 0.75 suitable) and suboptimum (i.e., ≤ 0.75 suitable) habitat areas were calculated for each modeled discharge. These results are provided to allow the evaluation of not only quantity but the spatial quality of habitat for TWR over the range of simulated flows.

Non-native Vegetation Control

One of the identified EARIP mitigation measures tied to the proposed minimum flow regime during the drought of record is non-native vegetation control. *H.verticillata* and *H. polysperma* were selected for removal because they were two of the three exotic species with a relative abundance >1% of total vegetation within the San Marcos River (see Table 7). *Colocasia esculenta* was the third exotic species with a relative abundance >1% but was excluded from analysis due to the lack of habitat suitability information available for this species. Two basic but highly conservative approaches were taken in the assessment. The first considers only non-native vegetation control from within existing occupied optimal TWR stands, while the second considers removal of non-natives within a 2 meter buffer of occupied optimal TWR stands but constrained by requiring TWR having a greater combined suitability than the suitability of the target non-native species. Figure 10 is provided to illustrate an example of the vegetation mapping keyed to TWR and non-native vegetation used as input to the analysis of non-native vegetation control as explained below.

Table 7. Vegetation species mapped in 2009 for the San Marcos River, their area coverage (m2) and relative abundance (%). Asterisks denote exotic vegetation species.

Species	Common Name	Area Coverage (m^2)	Relative Abundance (%)
*Hydrilla verticillata**	Hydrilla	14,785	26.63
*Colocasia esculenta**	Elephant ear	14,079	25.36
*Hygrophila polysperma**	East Indian Swampweed	12,001	21.62
Potamogeton illinoensis	Pondweed	3,384	6.10
Cabomba caroliniana	fanwort	3,278	5.90
Zizania texana	Texas wild rice	2,664	4.80
Sagittaria platyphylla	Arrow head	2,405	4.33
Ceratophyllum demersum	Coontail	633	1.14
*Nasturtium officinale**	Water cress	437	0.79
Heteranthera dubia	Water star grass	300	0.54
Nuphar advena	Cowlily	293	0.53
*Limnophila sessiliflora**	Ambulia	200	0.36
Riccia fluitans	Crystal wort	200	0.36
*Vallisneria spiralis**	Tape grass	139	0.25
Cyperus sp.		136	0.24
Hydrocotyle sp.	Pennywort	131	0.24
Grass sp.		116	0.21
*Eichhornia crassipes**	Water hyacinth	81	0.15
Ludwigia repens	Round leaf seedbox	60	0.11
Algae sp.		47	0.08
*Xanthosoma sagittifolium**	Giant elephant ear	40	0.07
*Pistia stratiotes**	Water lettuce	38	0.07
Myriophyllum	Variable leaved Milfoil	38	0.07
Polygonum sp.	Smart weed	28	0.05

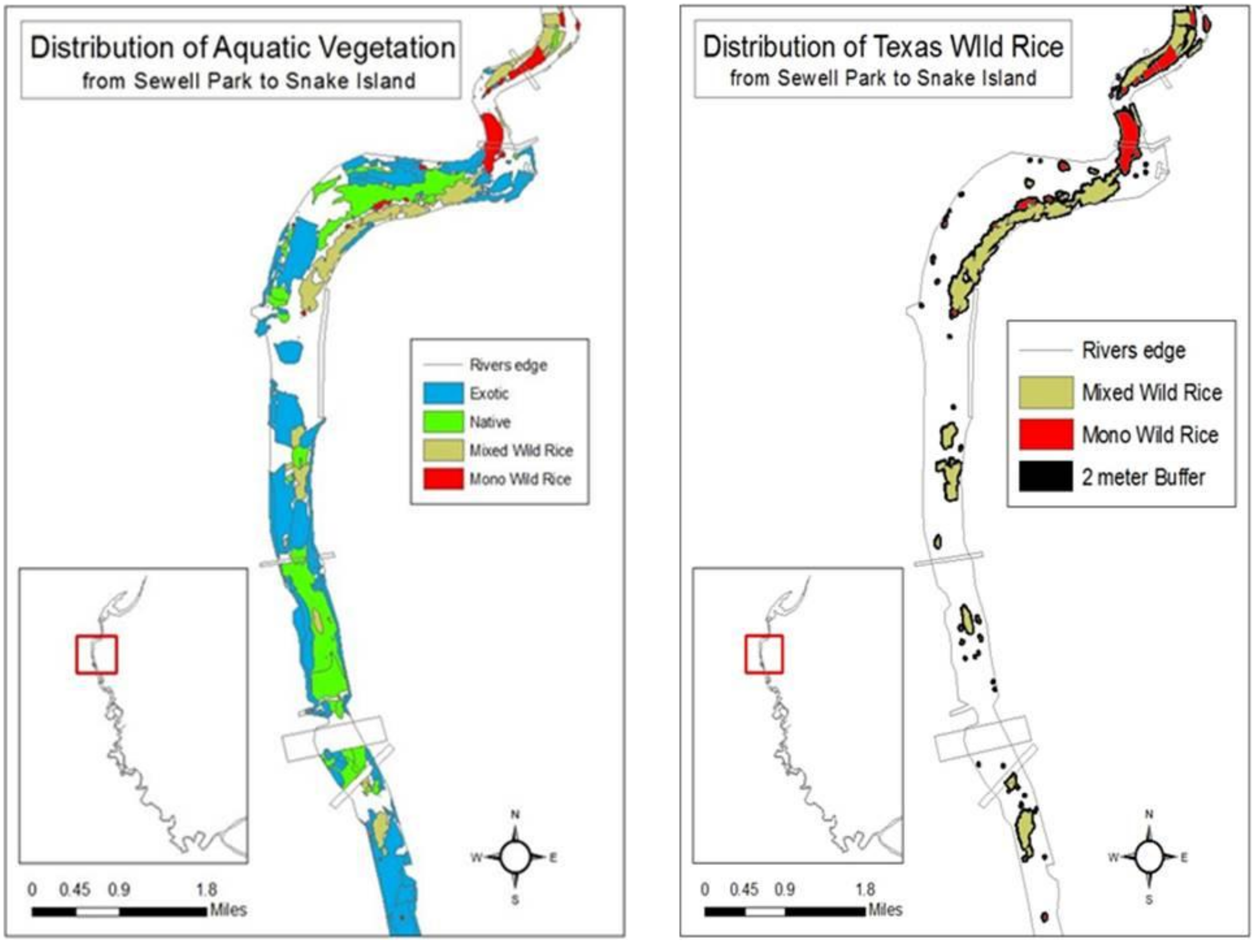


Figure 10. Vegetation mapping examples coded for the assessment of non-native vegetation control within the San Marcos River.

Non-native Vegetation Control - Removal of Hydrilla verticillata and Hygrophila polysperma from within Optimal Occupied TWR Patches

In this analysis, we assumed a highly restrictive approach of practical vegetation control where only *H. verticillata*and *H. polysperma*existing within occupied optimal TWR mixed vegetation stands would be removed. The underlying assumption is that TWR currently occupying locations with optimal depth and velocity conditions would have a high probability of expansion into the open substrate area with removal of the non-native plants

For each modeled discharge, vegetation polygons containing occupied optimal TWR conditions based on the distribution of 2009 mapped locations and having *H. veticillata* and *H. polysperma* were selected. The area of each patch was multiplied by the percentage of area occupied by *H. verticillata* and *H. polysperma* and then summed. Figure 11 provides a conceptual overview of the calculations for non-native vegetation removal from within TWR occupied optimal areas.

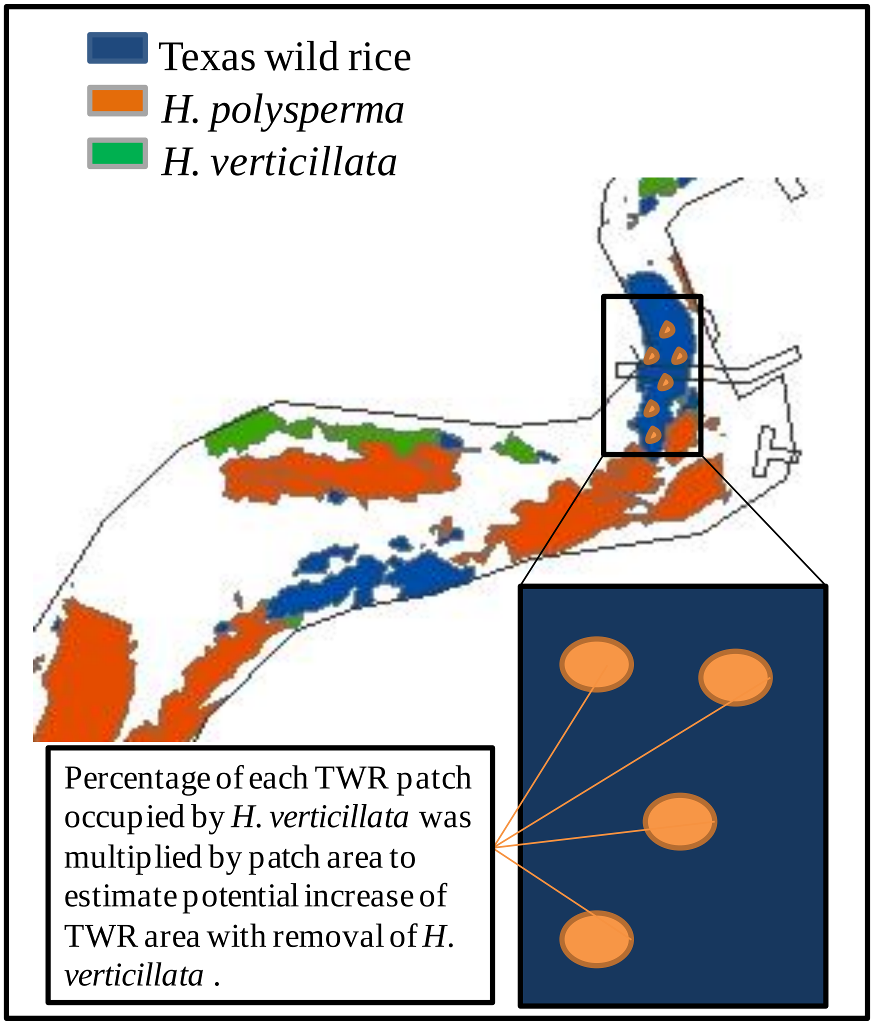


Figure 11. **Illustration explaining removal of H. verticalla and H. polysperma within predicted optimum and occupied TWR patches.**

Non-native Vegetation Control - Removal of Hydrilla verticillata and Hygrophila polysperma from 2 meter buffer adjacent to occupied optimal TWR Patches

ArcView 9.2 was used to create a 2 m buffer around each occupied optimal TWR patch at each modeled discharge. Within each 2 m buffer area at a given discharge, the current velocity and depth suitability curves for TWR, *H. verticillata* and *H. polysperma* were used to compute each species combined suitability. Only if TWR had the highest combined suitability within the 2 meter buffer currently occupied by either *H. verticillata* or *H. polysperma* was the area included as potential TWR area expansion. Figure 12 provides a conceptual example of the analytical approach to the calculation. The basic assumption is that if the non-native vegetation was removed from areas adjacent to occupied and optimal TWR stands and those areas maintained a higher combined suitability for TWR relative to the either *H. verticillata* or *H. polysperma* that TWR would have a competitive advantage to occupy the exposed substrate. Figure 12 is provided to illustrate the base vegetation layer maps utilized for these two basic analyses.

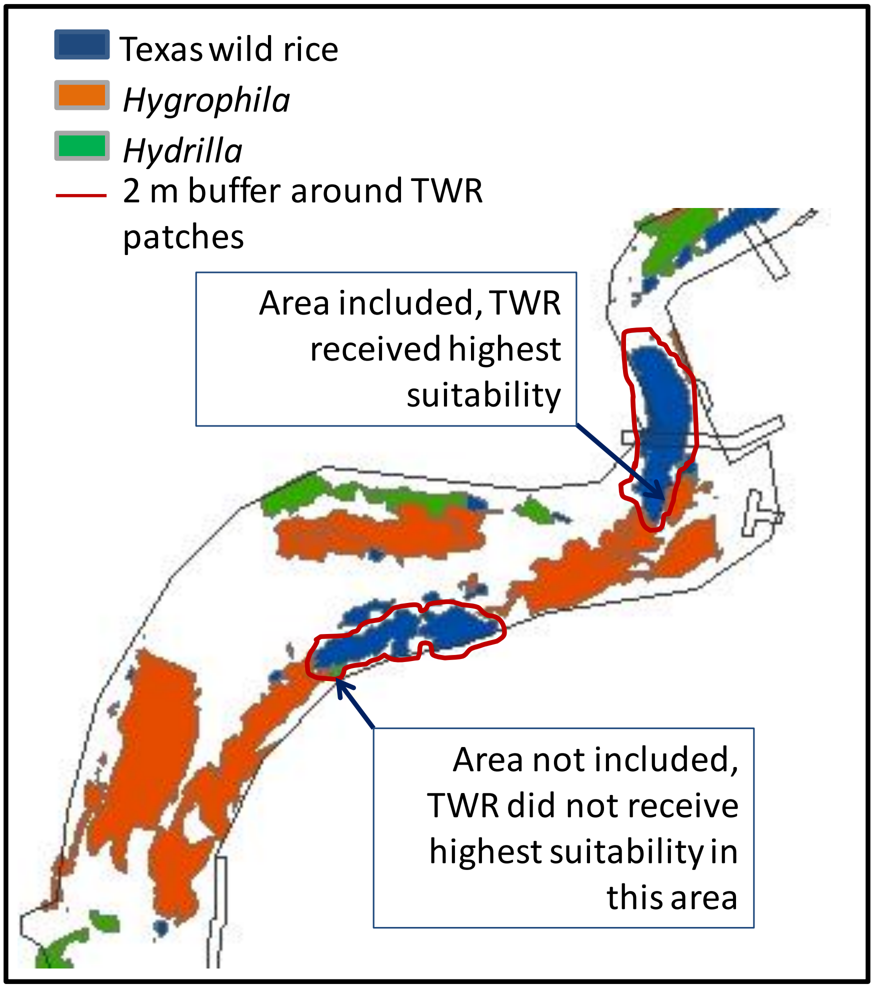


Figure 12. Illustration explaining removal of H. verticalla and H. polysperma adjacent to predicted optimum and occupied TWR patches where TWR has a greater combined suitability compared to the non-native species.

Temperature Modeling

Physical habitat (i.e., WUA) is a necessary but not sufficient condition for suitable habitat for aquatic resources. Previous studies and modeling efforts have identified that a critical component of the evaluation of the proposed flow regimes in the Comal and San Marcos River systems is related to thermal affects on darter reproduction (among other factors and species). Laboratory studies have suggested that at 78.8 (F) there is an increased rate of larval mortality for darters; at 86 (F) egg production is curtailed, and at 94.6 (F) thermal death can be expected. Given the potential combination of low flows and high summer temperatures, a critical evaluation of thermal conditions is required. A fundamental premise of the proposed drought of record minimum flow regimes is that darters are able to reproduce year-round and therefore maintaining conditions that avoid thermal death and minimize temperatures that would result in either loss of egg production or increased larval mortality rates for adequate areas within the river should not exceed a 6 month period and that the increased pulse flows over the remaining 6 months would provide conditions suitable for expanded darter reproduction and recruitment. The assessment of thermal conditions within the Comal and San Marcos River systems was approached using updated calibrations of the existing Qual2e water quality models for both river systems using dynamic simulations on an hourly basis as described below.

Comal Water Temperature Modeling

Model Structure

The original Qual2E model developed by Hardy et al. (1998) was revised and recalibrated to 2009 hourly data based on updated information on spring discharge relationships and water temperature collected over the last decade. The physical structure of the computational elements was retained as were the number and location of various headwater (7) and point loads (44) representing various springs within Landa Lake. Headwaters consisted of:

1. The NE Branch (Reach 1 – Bleeders Creek),
2. NW Branch (Reach 2),
3. Spring Run 1 (Reach 6),
4. Spring Run 2 (Reach 9),
5. Spring Run 3 (Reach 8),
6. Old Channel outlet (Reach 17) and,
7. The Spring Fed Pool outlet (Reach 16).

Point loads for Landa Lake springs were taken from the spatial mapping provided in Brune (1981) and assigned to the nearest computational element and their locations remained unchanged from the original model formulation in Hardy et al. (1998). Figure 13 shows the Qual2E reaches for reference to specific locations.

Assumed Spring Flows for Comal Headwater and Point Loads

As an initial step in modeling water temperatures in the Comal River, the assumed flow rates for specific springs as a function of total Comal River discharge were reexamined. Previous modeling efforts (Hardy, 2009; Hardy et al., 1998) assumed a flow break between 'high' versus 'low' total Comal River discharges at 126 cfs with the following assumptions for specific spring location discharges based on limited field observations using synoptic flows in the late 1990's and the spring size classification outlined in Brune (1981) as indicated in Table 8.

Table 8. Historically assumed Qual2e spring discharge distributions for high versus low flow conditions.

Assumptions:	
Above breakpoint	**Below breakpoint**
Spring run 1 is 9.9% of total	
Spring run 2 is 1.4% of total	
Spring run 3 is 12.3% of total	Spring run 3 is 3 cfs.
NE branch, spring run 4, is 2.5% of total	NE branch, spring run 4, is 0.25 cfs
Spring run 5 is 0.45% of total	Spring run 5 shuts down (0 cfs)
Spring Island (QUAL2E Section 4, Segment 5) is 0.4 cfs.	Spring Island (QUAL2E Section 4, Segment 5) is 0.1 cfs.
Therefore spring runs account for 25.55% of total springflow.	Otherwise, flow above USFWS/TPWD LL6 (QUAL2E Section 4, segment 2) sums to 10 cfs.
Headwater for northeast branch (Blieder's Creek) will have 1% of total	Headwater for northeast branch (Blieder's Creek) will have 0.25 cfs
Old channel, woods section headwater is always 25.5 cfs, down to Qt = 30 cfs	Old channel, woods section headwater is always 25.5 cfs, down to Qt = 30 cfs
Old channel, spring fed pool headwater is always 9.5 cfs.	Old channel, spring fed pool headwater is always 9.5 cfs.

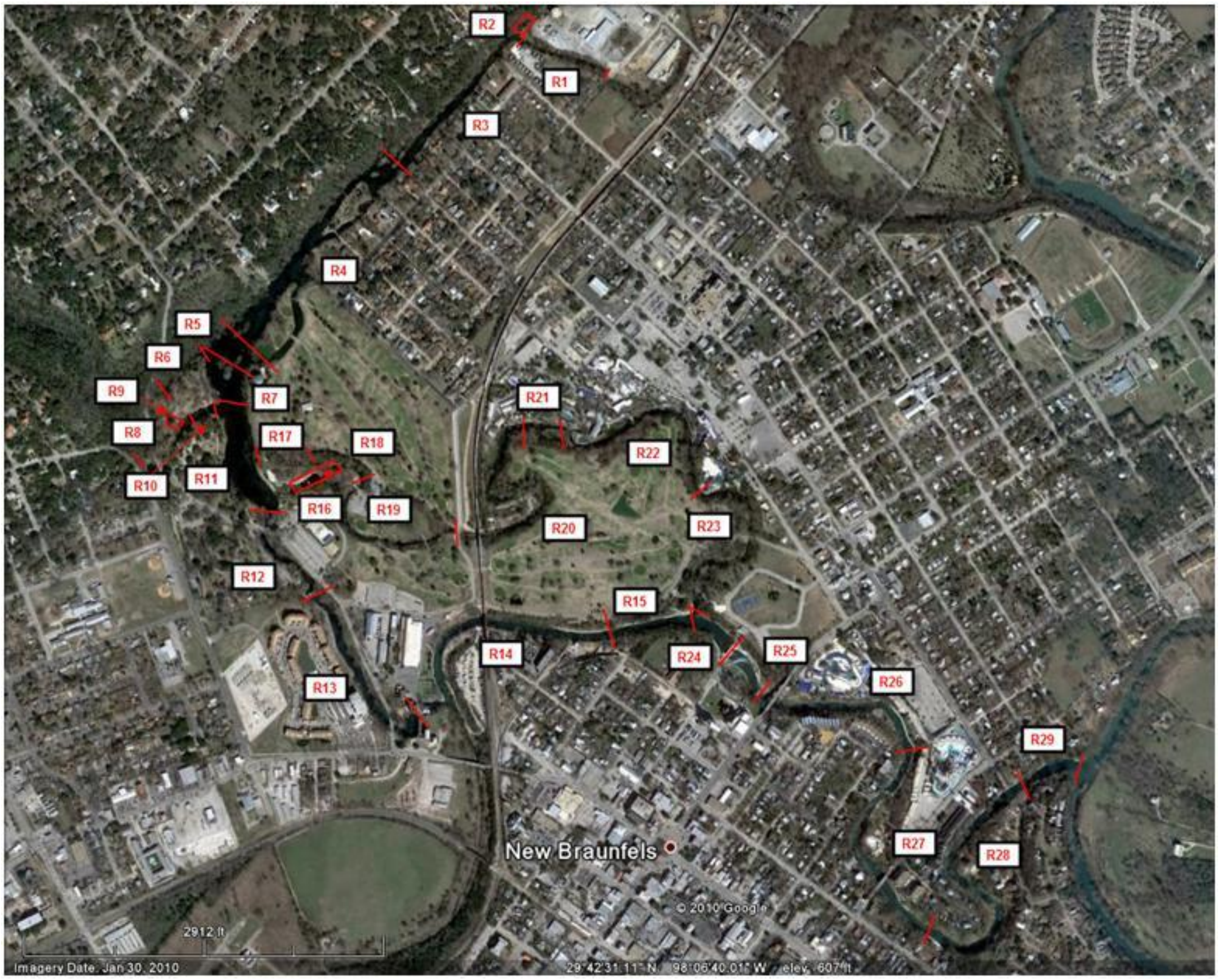


Figure 13. Qual2e computational river reaches used in modeling the Comal River System.

However, more extensive field monitoring conducted by EAA over the past 8 years and the work of Guyton Associates (2004) suggested that these assumptions needed to be revised to reflect existing knowledge of the spring flow dynamics. Table x.1 shows the measured contribution of the main spring runs for a range of observed total Comal River discharge (BioWest 2010a).

These data indicate that on average for these flow ranges the total contribution of the main spring runs to the total Comal River discharge is on the order of 25 percent. The data also suggest that as the total Comal River discharge decreases, the total contribution of the main spring runs begins to decrease and that there is a differential reduction between the specific spring runs. Unfortunately, no quantitative data exist on the differential spring run contributions below these flows over the discharge ranges being evaluated by the EARIP.

The analysis by Guyton Associates (2004) of historical water levels and spring flows was used as a basis for estimating main spring run discharges under lower flow conditions. Figure 14 shows the relationship between the Landa Park well levels versus total Comal Springs flow for the 1948 to 2001 period (Guyton Associates, 2004).

Table 9. Total Comal River discharge and the percent contribution of main spring runs.

Total Comal River Flow (cfs)	Spring #1 (%) of Total Flow	Spring #2 (%) of Total Flow	Spring #3 upper (%) of Total Flow	Spring #3 lower (%) of Total Flow	Spring Flow as Percent of Total Comal Flow
159	4.80	3.50	4.70	13.60	21.90
224	6.90	1.50	5.10	11.50	19.90
259	9.50	1.30	5.60	13.00	23.80
286	7.90	2.10	4.20	13.00	23.00
295	9.30	1.30	9.60	12.30	22.90
330	9.70	1.50	4.80	12.10	23.30
351	7.10	1.10	2.50	9.10	17.30
361	11.80	1.70	10.40	13.70	27.20
368	10.20	1.40	9.20	11.90	23.50
375	11.50	1.70	9.80	13.20	26.40
377	13.30	2.30	11.10	13.90	29.50
385	11.20	1.50	9.70	12.30	25.00
405	12.10	1.80	9.90	13.20	27.10
411	12.20	1.80	10.30	13.30	27.30
424	10.00	1.50	3.50	12.30	23.80
446	14.40	2.40	10.20	13.20	30.00
Averages					
341	10.12	1.78	7.54	12.60	24.49

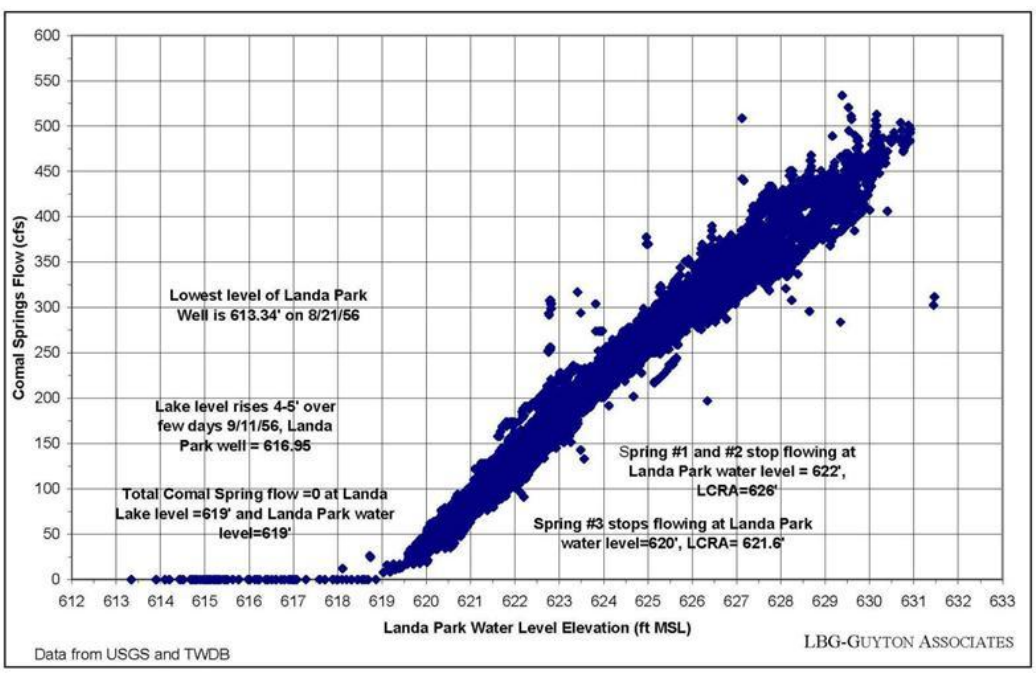


Figure 14. **Relationship between the Landa Park well level versus Comal Springs flows for the 1948 to 2001 period (Guyton Associates, 2004).**

These results show that historically Spring #1 and #2 stop flowing at a discharge that ranges between approximately 150 to 100 cfs and that Spring #3 stops flowing at a discharge range between approximately 60 and 20 cfs based on the measured water surface elevations. We therefore assumed that as flows drop below the observed flow ranges reported in Table 9, flow contributions from the main spring runs will diminish to a point that all flow will be provided by the springs within Landa Lake proper and primarily along the western shore margin near the main spring runs and from various spring locations in the vicinity of Spring Island and Pecan Islands (Brune, 1981; Guyton Associates, 2004).

For the purposes of modeling, it was assumed that Springs #1 and #2 would stop flowing at a total Comal River discharge of 130 cfs and that Spring #3 would stop flowing at a total Comal River discharge of 50 cfs (Figure 14). The percent contributions for each main spring run were initially set to the values associated with a total Comal River flow of 160 cfs, which is equivalent to the lowest observed discharge listed in Table 9. The percent contributions were assumed to linearly decrease to zero at the flow rates where springs were assumed to stop flowing. However, due to analytical constraints on headwater elements within Qual2E, a nominal spring flow of 0.01 cfs was assigned to each main spring run (and headwater) for all simulated flow rates where springs or headwaters were assumed to have ceased flowing. Headwater inflows as a function of total Comal River discharge are provided in Table 10.

Table 10. Assumed headwater inflows (cfs) for each headwater as a function of total Comal River discharge.

Total Comal Discharge (cfs)	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160	165	170
HeadWaters Discharge (cfs)																														
NW_Branch	0.01	0.01	0.01	0.01	0.01	0.01	2.20	2.40	2.60	2.80	3.00	3.20	3.40	3.60	3.80	4.00	4.20	4.40	4.60	4.80	5.00	5.20	5.40	5.60	5.80	6.00	6.20	6.40	6.60	6.80
NE_Branch	0.01	0.01	0.01	0.01	0.01	0.01	0.06	0.06	0.07	0.07	0.08	0.08	0.09	0.09	0.10	0.10	0.11	0.11	0.12	0.12	0.13	0.13	0.14	0.14	0.15	0.15	0.16	0.16	0.17	0.17
Spring_Run_3	0.01	0.01	0.01	0.01	0.01	2.35	2.59	2.82	3.06	3.29	3.53	3.76	4.00	4.23	4.47	4.70	4.94	5.17	5.41	5.64	5.88	6.11	6.35	6.58	6.82	7.05	7.29	7.52	7.76	7.99
Spring_Run_1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	1.25	1.30	1.34	1.39	1.44	1.49	1.54	1.58	1.63
Spring_Run_2	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	2.28	2.36	2.45	2.54	2.63	2.71	2.80	2.89	2.98
OC-Woods (culvert)	10.50	14.00	17.50	21.00	24.50	28.00	31.50	35.00	38.50	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00
OC-SPring_fed_pool	4.50	6.00	7.50	9.00	10.50	12.00	13.50	15.00	16.50	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00

Flow contribution of the 44 point loads associated with various spring sources were estimated according to relative size as identified in Brune (1981), reported or assumed spring elevations based on bathymetry of Landa Lake, and as a factor of total Comal discharge. Guyton Associates (2004) estimated that Spring #3 stops flowing at a total Comal River discharge of approximately 50 cfs, which corresponds to an elevation of 620 feet. Based on Landa Lake bathymetry (Figure 15), headwaters in Reach 1 and 2 were set to 0.01 cfs for simulated flows below a total Comal River discharge of 50 cfs while spring sources (i.e., point loads) in Reach 2 and the first three point loads in Reach 3 were assigned a value of zero, since they are at an elevation above 620 feet. It is also assumed that at flows below 50 cfs, Spring #5 (Nolte Apartments) stops flowing since it is approximately six inches above the lake elevation. At total Comal River discharges above 50 cfs, point loads were proportionally increased based on their assumed size. Point load values for each simulated discharge are provided in Table 11. For all simulations, a constant water temperature of 74.51 (F) was assumed for headwater and point load sources with the exception of Reach 1 (Bleeders Creek) headwater inflows, which was assigned an initial value of 80.0 (F) based on temperature monitoring data for summer months.

Assumed Flow Splits for Old and New Channel

Previous modeling and annual monitoring has demonstrated that the old channel maintains the highest quality darter habitat, especially at lower flow rates. The old channel is also the target for protective mitigation measures during extreme low flow events. Therefore preference for partitioning of the flows was given to the old channel as shown in Table 12. For all simulated flows above 70 cfs, the flow in the old channel was maintained at 60 cfs. This maximum value was selected to avoid vegetation scour that has been observed at higher flow rates that can reduce both the quantity and quality of darter habitat in this section of the Comal River. For all other simulations, 70 percent of the flow into the old channel was assumed to be through the culverts (Reach 17) and the remaining 30 percent through the Spring Fed Pool (Reach 16).

Table 11. Assumed point load discharges for the Landa Lake utilized in the Qual2e modeling runs.

Total Comal Flow (cfs)	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160	165	170
Point Load Flow (cfs)																														
1	0.00	0.00	0.00	0.00	0.00	0.00	1.79	1.95	2.12	2.28	2.44	2.61	2.77	2.94	3.10	3.26	3.43	3.59	3.75	3.92	4.08	3.96	4.11	4.26	4.41	4.57	4.72	4.87	5.02	5.18
2	0.00	0.00	0.00	0.00	0.00	0.00	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
3	0.00	0.00	0.00	0.00	0.00	0.00	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
4	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.69	0.75	0.81	0.87	0.93	0.98	1.04	1.10	1.16	1.22	1.28	1.34	1.40	1.45	1.21	1.25	1.30	1.35	1.40	1.44	1.49	1.54	1.58
5	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
6	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
7	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
8	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
9	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
10	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
11	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
12	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
13	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
14	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
15	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
16	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
17	0.23	0.28	0.33	0.37	0.42	0.26	1.24	1.35	1.47	1.58	1.70	1.81	1.92	2.04	2.15	2.27	2.38	2.49	2.61	2.72	2.83	2.66	2.76	2.86	2.97	3.07	3.17	3.28	3.38	3.48
18	1.48	1.77	2.07	2.36	2.66	2.75	0.47	0.51	0.56	0.60	0.64	0.69	0.73	0.78	0.82	0.86	0.91	0.95	0.99	1.04	1.08	0.84	0.87	0.90	0.93	0.97	1.00	1.03	1.06	1.10
19	1.48	1.77	2.07	2.36	2.66	2.75	0.47	0.51	0.56	0.60	0.64	0.69	0.73	0.78	0.82	0.86	0.91	0.95	0.99	1.04	1.08	0.84	0.87	0.90	0.93	0.97	1.00	1.03	1.06	1.10
20	0.35	0.42	0.49	0.56	0.64	0.50	0.81	0.85	0.89	0.93	0.97	1.01	1.05	1.09	1.12	1.16	1.20	1.24	1.28	1.32	1.36	1.11	1.13	1.16	1.19	1.22	1.24	1.27	1.30	1.33
21	1.48	1.77	2.07	2.36	2.66	2.75	0.47	0.51	0.56	0.60	0.64	0.69	0.73	0.78	0.82	0.86	0.91	0.95	0.99	1.04	1.08	0.84	0.87	0.90	0.93	0.97	1.00	1.03	1.06	1.10
22	1.48	1.77	2.07	2.36	2.66	2.75	0.47	0.51	0.56	0.60	0.64	0.69	0.73	0.78	0.82	0.86	0.91	0.95	0.99	1.04	1.08	0.84	0.87	0.90	0.93	0.97	1.00	1.03	1.06	1.10
23	1.48	1.77	2.07	2.36	2.66	2.75	0.47	0.51	0.56	0.60	0.64	0.69	0.73	0.78	0.82	0.86	0.91	0.95	0.99	1.04	1.08	0.84	0.87	0.90	0.93	0.97	1.00	1.03	1.06	1.10
24	1.48	1.77	2.07	2.36	2.66	2.75	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
25	1.48	1.77	2.07	2.36	2.66	2.75	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
26	0.91	1.09	1.27	1.46	1.64	1.62	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
27	0.91	1.09	1.27	1.46	1.64	1.62	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
28	0.91	1.09	1.27	1.46	1.64	1.62	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
29	0.91	1.09	1.27	1.46	1.64	1.62	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
30	0.91	1.09	1.27	1.46	1.64	1.62	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
31	0.91	1.09	1.27	1.46	1.64	1.62	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
32	0.91	1.09	1.27	1.46	1.64	1.62	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
33	0.91	1.09	1.27	1.46	1.64	1.62	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
34	0.91	1.09	1.27	1.46	1.64	1.62	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
35	0.91	1.09	1.27	1.46	1.64	1.62	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
36	0.91	1.09	1.27	1.46	1.64	1.62	1.33	1.45	1.57	1.70	1.82	1.94	2.06	2.19	2.31	2.43	2.55	2.67	2.80	2.92	3.04	2.87	2.98	3.10	3.21	3.32	3.43	3.54	3.65	3.76
37	0.01	0.01	0.01	0.01	0.01	2.23	2.45	2.67	2.89	3.12	3.34	3.56	3.78	4.01	4.23	4.45	4.67	4.90	5.12	5.34	5.56	5.79	6.01	6.23	6.45	6.68	6.90	7.12	7.34	7.57
38	0.01	0.01	0.01	0.01	0.01	2.23	2.45	2.67	2.89	3.12	3.34	3.56	3.78	4.01	4.23	4.45	4.67	4.90	5.12	5.34	5.56	5.79	6.01	6.23	6.45	6.68	6.90	7.12	7.34	7.57
39	0.93	1.12	1.31	1.49	1.68	1.87	3.30	3.60	3.90	4.20	4.50	4.80	5.10	5.40	5.70	6.00	6.30	6.60	6.90	7.20	7.50	7.80	8.10	8.40	8.70	9.00	9.30	9.60	9.90	10.20
40	0.23	0.28	0.33	0.37	0.42	0.26	0.42	0.46	0.50	0.54	0.58	0.62	0.66	0.70	0.73	0.77	0.81	0.85	0.89	0.93	0.97	2.98	3.10	3.21	3.33	3.44	3.56	3.67	3.79	3.90
41	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	1.25	1.30	1.34	1.39	1.44	1.49	1.54	1.58	1.63
42	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	1.25	1.30	1.34	1.39	1.44	1.49	1.54	1.58	1.63
43	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	1.25	1.30	1.34	1.39	1.44	1.49	1.54	1.58	1.63
44	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	1.25	1.30	1.34	1.39	1.44	1.49	1.54	1.58	1.63

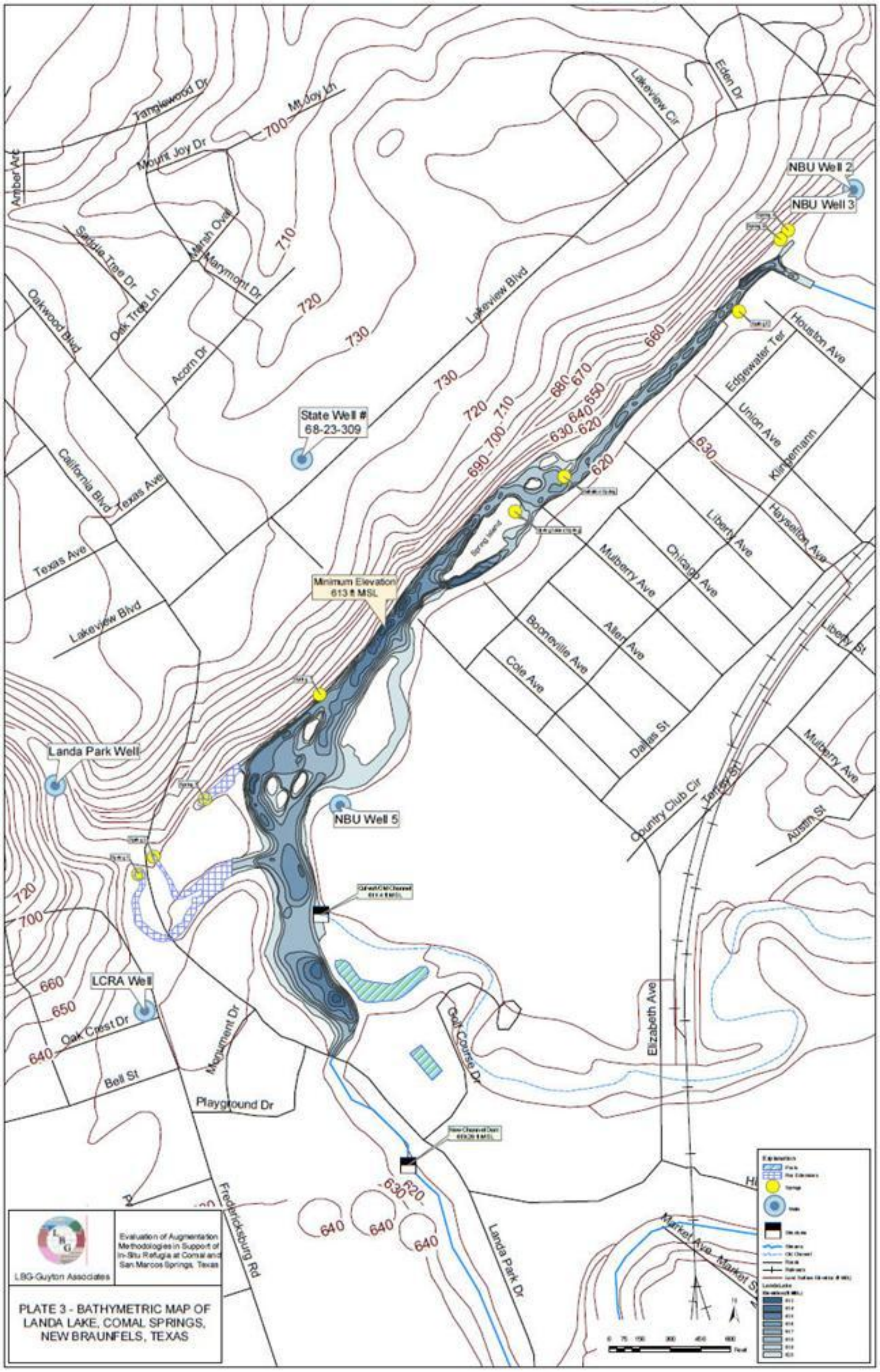


Figure 15. **Landa Lake bathymetry and main spring locations (source: Guyton Associates 2004).**

Table 12. Assumed Flow Splits in the Old Channel for Total Flow Rates in the Comal River. (Note: 60 cfs is assumed to be in the old channel at all total Comal River discharges above 70 cfs).

Total Comal River Discharge (cfs)	Old Channel Flow (cfs)
25	15
30	20
35	25
40	30
45	35
50	40
55	45
60	50
65	55
70	60

Climate Data and Model Calibration

The 2009 calendar year meteorological data from the New Braunfels Airport was utilized for calibration and simulation. The 2009 data set was chosen because it represented an extended hot and dry condition during the low flow summer period and empirical water temperature data was available for key locations within the Comal River for the purpose of model calibration (Figure 16). Calibration of the water temperature model focused on the July period as this coincided with both low flows and highest observed water and air temperatures.

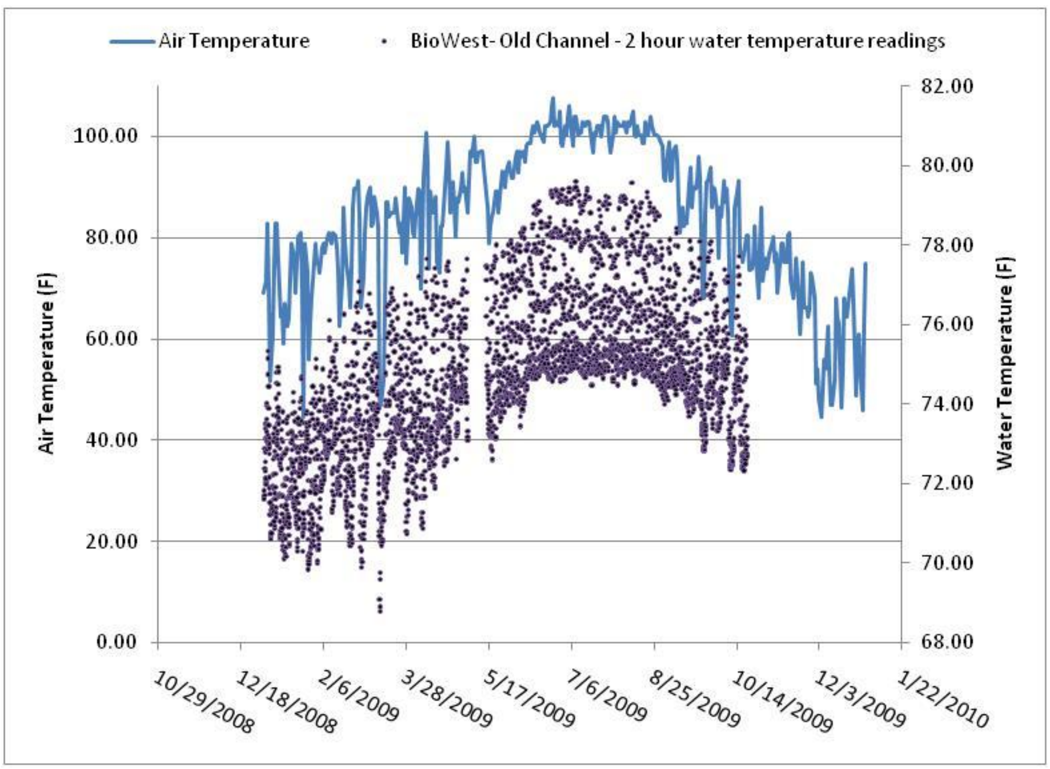


Figure 16. Maximum Daily Air Temperature and 2 hour interval recorded water temperatures from the Comal River in the old channel (BioWest thermograph data).

Figure 17 shows the daily discharge for 2009 at the USGS gage on the Comal River and illustrates that the July 2009 period maintained consistent low flows around 165 cfs. July was therefore chosen as the basis for comparison of flow impacts based on the consistent low flow and concurrent high air temperatures. Water temperature data from the USGS at Landa Lake and the old channel as well as 2 hour interval thermograph data collected at several locations by BioWest were used for model calibration. Net solar radiation, fraction of cloud cover, dry bulb temperature, wet bulb temperature, barometric pressure and wind speed were collated into the required 8 - 3 hour blocks for each 24 hour period for July 2009. Qual2E was run in dynamic simulation mode to estimate the hourly water temperatures and compared to the available thermograph data at key locations within Comal River system. Initial calibration runs were made at a total Comal River discharge of 165 cfs as this was the July 2009 average discharge and flows in the old channel were set to 45 cfs based on measurements by BioWest on July 2nd, 2009.

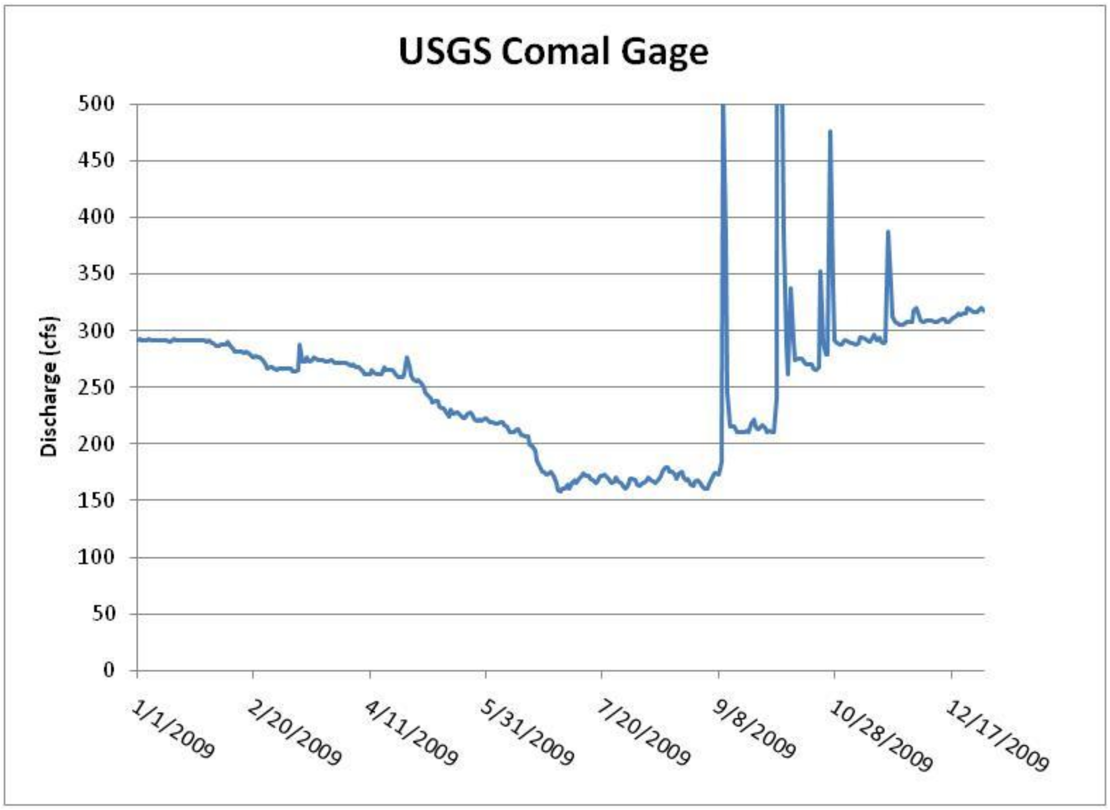


Figure 17. Mean daily discharge in the Comal River at the USGS Gage for 2009.

Figures 18 through 20 provide the predicted versus observed hourly water temperatures at three locations within the Comal River system. The results demonstrate that the simulated water temperatures at the calibration flows (old and new channel) are within approximately 1.0 to 0.5 degrees (F) over the entire 31 day simulation period. The calibrated Qual2e model was used to simulate the hourly temperatures throughout the Comal River based on a range of simulated flows and flow split assumptions between the old and new channel as noted above. In order to simplify the interpretation of the evaluation, flow scenarios were simulated for the July 2009 period but only the daily results for July 15th are utilized for explanatory purposes. We believe this simplification is justified based on the consistency of the results over the entire monthly period as shown in the previous figures.

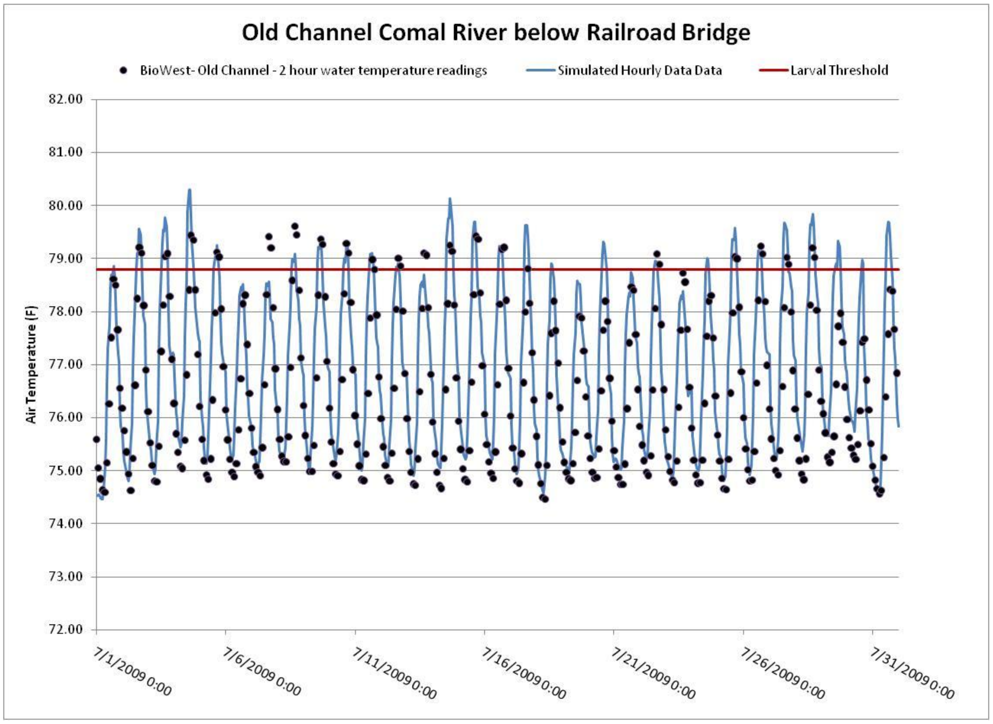


Figure 18. Simulated and observed water temperatures in the Old Channel of the Comal River during July 2009.

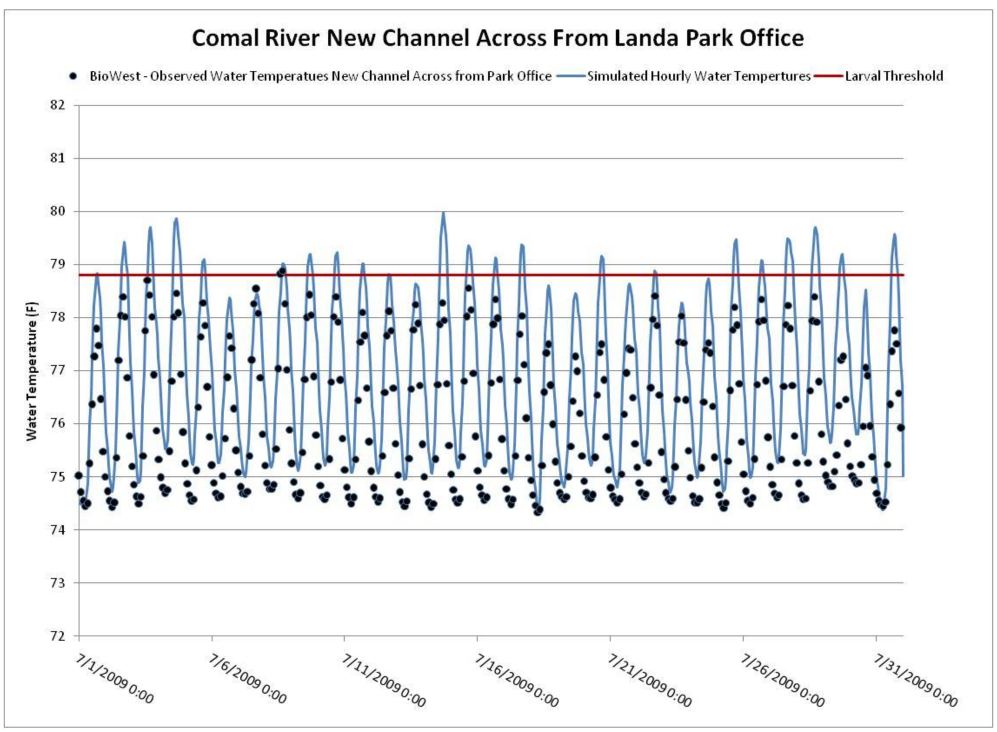


Figure 19. Simulated and Observed Water Temperatures in the New Channel of the Comal River during July 2009.

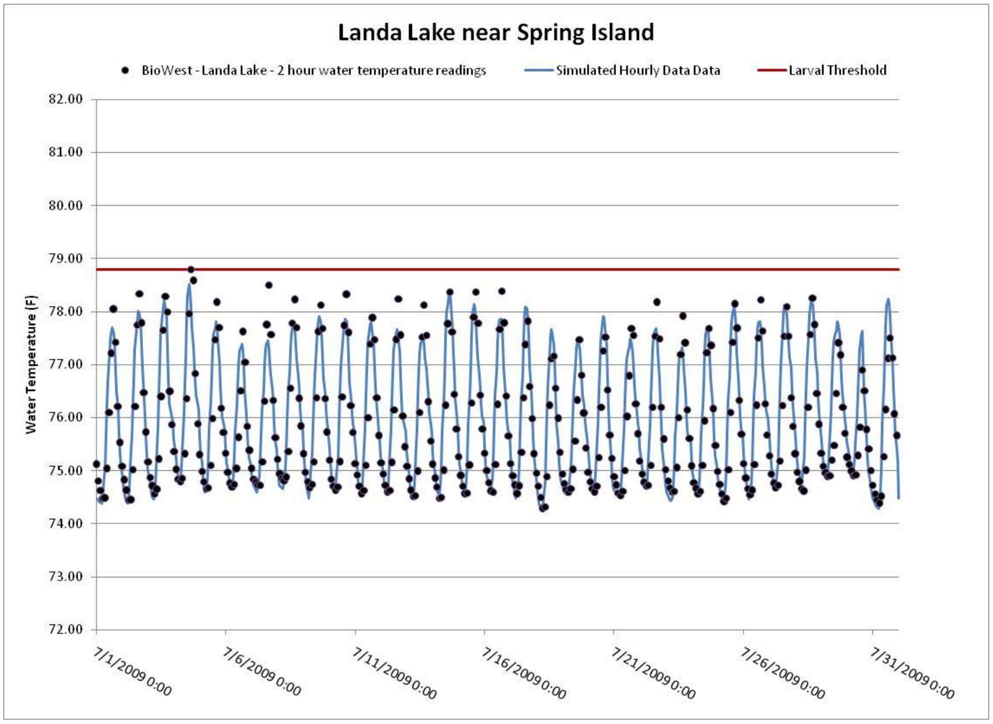


Figure 20. Simulated and observed water temperatures in Landa Lake near Spring Island during July 2009.

San Marcos Water Temperature Modeling

Model Structure

The original Qual2E model developed by Bartsch et al. (2000) was revised and recalibrated to 2009 hourly data based on updated information on flows and water temperature collected over the last decade. The physical structure of the computational elements was retained with 21 designated reaches (Figure 21). Sessoms Creek was added as a point load and the discharge of the San Marcos wastewater treatment plant was changed from the maximum design flow rate of ~ 27 cfs to the reported 2009 annual average daily flow of 6.5 cfs. The model structure contains 4 headwater elements and 4 point loads as follows:

1. Spring Lake Headwater (Reach 1),
2. Spring Lake Slough Headwater (Reach 2),
3. Glover's Ditch Headwater (Reach 10),
4. Mill Race Diversion Headwater (Reach 14),

1. Sessoms Creek Point load,
2. Mill Race Discharge Point load,
3. State Fish Hatchery Point load,
4. San Marcos Wastewater Treatment Plant Point load

Assumed Spring Flows for San Marcos Headwater and Point Loads

Individual spring flows within Spring Lake were treated as a single incremental inflow within Reach 1. This approach within Qual2e assumes that the total discharge is distributed along the entire reach length which closely approximates the spatial distribution of springs as shown in Figure 22. This is considered a pragmatic assumption given the available data on spring flows (Guyton Associates, 2004) and lack of quantitative data on individual spring flow discharges with changes in total San Marcos River discharge. Changes in total San Marcos discharge were modeled by changes to the headwaters and incremental inflow values within Reach 1 as shown in Table 13.

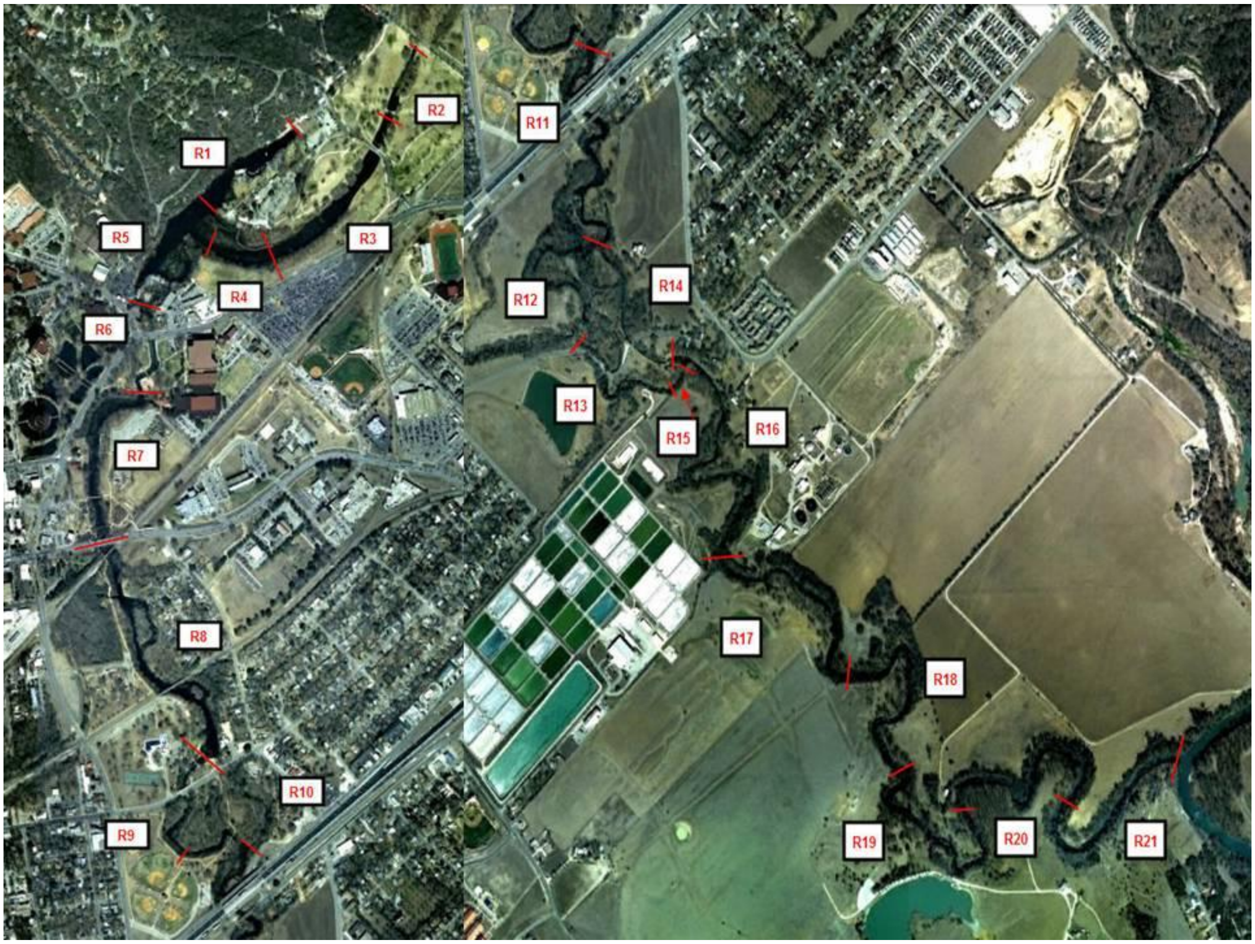


Figure 21. Qual2e computational river reaches used in modeling the San Marcos River System.

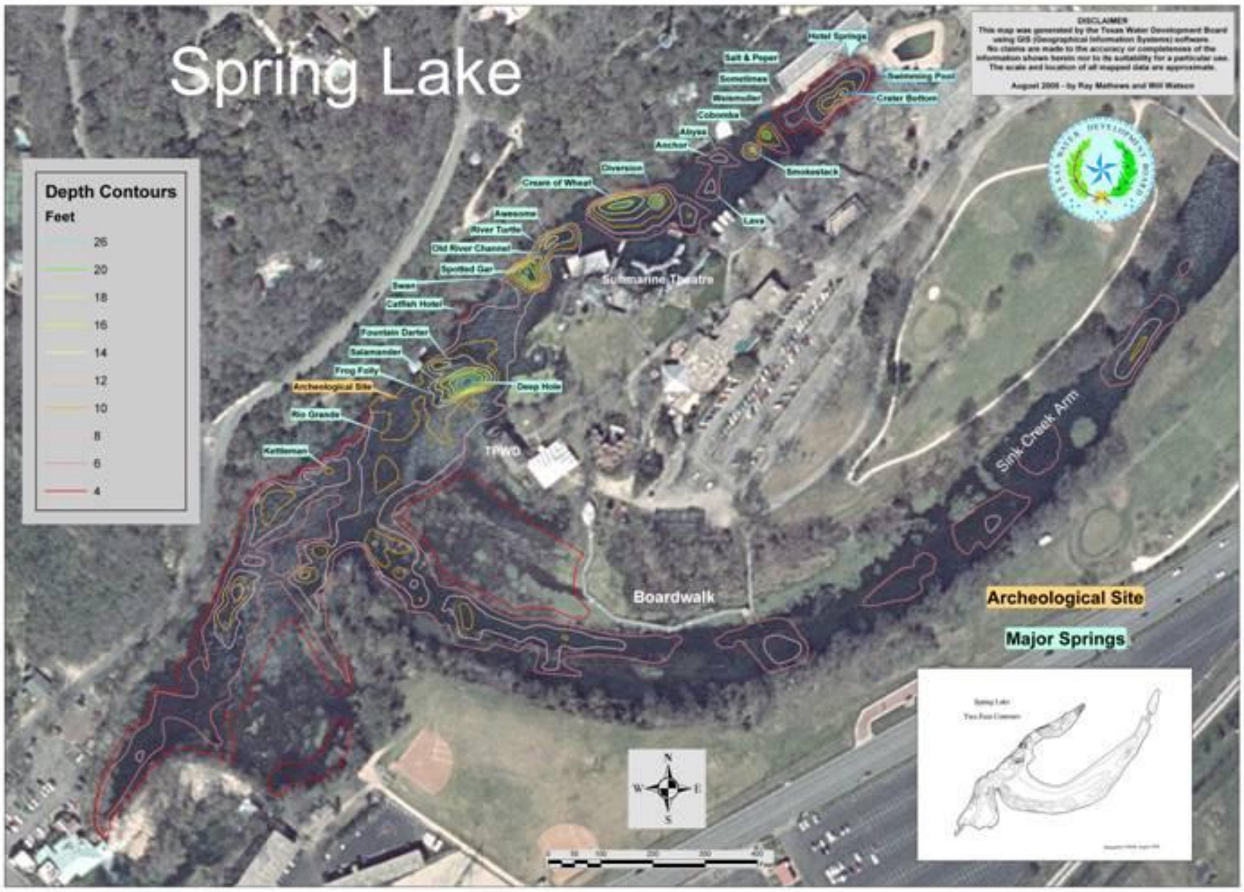


Figure 22. Spatial location of principal springs within Spring Lake, San Marcos River system. Adapted from TWDB 2005.

Table 13. Assumed headwater and point load discharges for the San Marcos River.

San Marcos Discharge (cfs)	45	50	55	60	65	70	75	80	85	90	100	110	120	130
Spring Lake Headwater	3.1	3.4	3.8	4.1	4.4	4.8	5.1	5.5	5.8	6.1	6.8	7.5	8.2	8.9
Incremental Inflow Reach 1	41.9	46.6	51.3	55.9	60.6	65.2	69.9	74.5	79.2	83.9	93.2	102.5	111.8	121.1
Spring Lake Slough	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sessoms Creek	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
State Fish Hatchery	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Wastewater Plant	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6

Climate Data and Model Calibration

The 2009 calendar year meteorological data from the New Braunfels Airport was utilized for calibration and simulation. The 2009 data set was chosen because it represented an extended hot and dry condition during the low flow summer period and empirical water temperature data was available for key locations within the Comal River for the purpose of model calibration (Figure 23). Calibration of the water temperature model focused on the July period as this coincided with both low flows and highest observed water and air temperatures. As shown in Figure 23, the water temperature response closely tracks the variation in weather data at the New Braunfels Airport and therefore the weather data from this location was used in the calibration and simulations rather than equivalent data from the San Marcos Airport. We believe this is further justified in that it provides a single weather trace for use in the assessments rather than added complexity due to different weather data, the close proximity of these two locations, and the uncertainties in the estimated discharges for the proposed drought of record target flow regime.

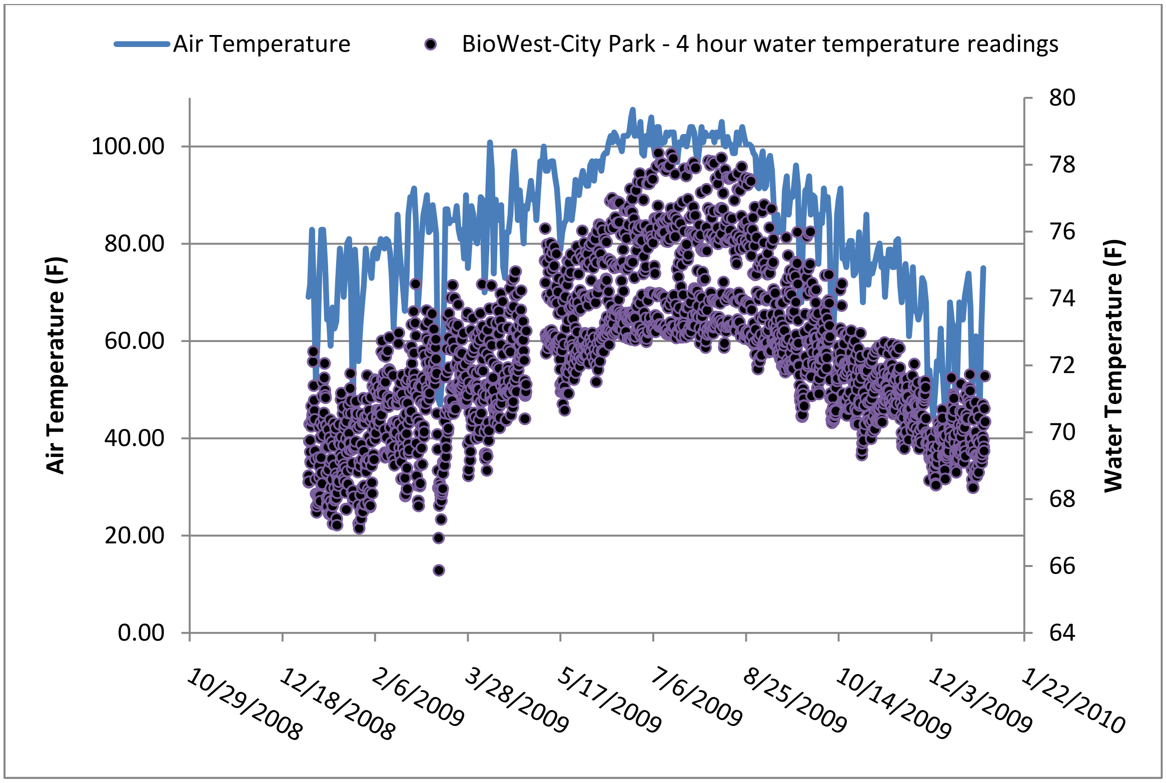


Figure 23. **Maximum Daily Air Temperature and 4 hour interval recorded water temperatures from the San Marcos River at City Park (BioWest thermograph data).**

Figure 24 shows the daily discharge for 2009 at the USGS gage on the San Marcos River and illustrates that the July 2009 period maintained consistent low flows around 89 cfs. July was therefore chosen as the basis for comparison of flow impacts based on the consistent low flow and concurrent high air temperatures. Water temperature comprised of 4 hour interval thermograph data collected at several locations by BioWest were used for model calibration.

Figures 25 through 28 provide the predicted versus observed hourly water temperatures at four key locations within the San Marcos River system. Note that the thermograph data was provided in 4 hour increments rather than 2 hour incremental values as in the Comal River. The results demonstrate that the simulated water temperatures at the calibration flows are within approximately 0.5 to 1.5 degrees (F) over the entire 31 day simulation period at these locations. It should be noted, that there is a slight over estimation of the maximum daily temperatures in the City Park and Thompson Island reaches of the San Marcos. The calibrated Qual2e model was used to simulate the hourly temperatures throughout the San Marcos River based on a range of simulated discharges. In order to simplify the interpretation of the evaluation, flow scenarios were simulated for the July 2009 period but only the daily results for July 15th are utilized for explanatory purposes. We believe this simplification is justified based on the consistency of the results over the entire monthly period as shown in the previous figures.

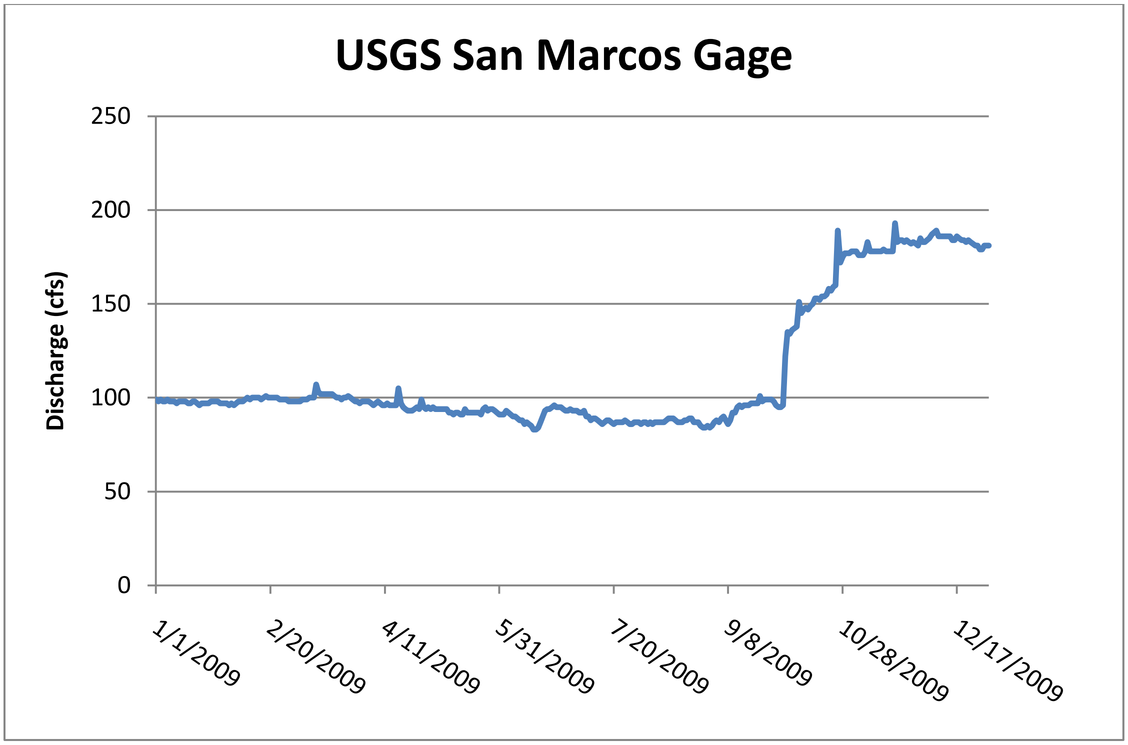


Figure 24. Mean daily discharge in the San Marcos River at the USGS Gage for 2009.

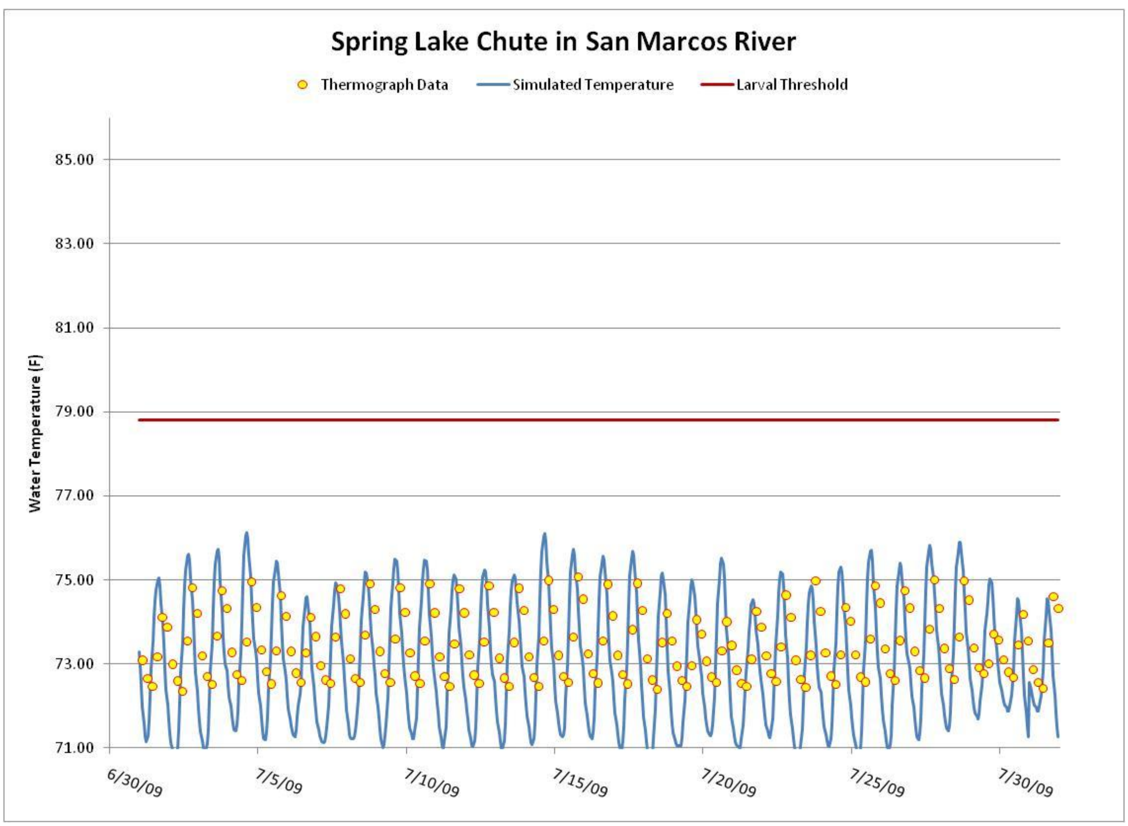


Figure 25. Simulated and observed water temperatures at the end of Spring Lake (Chute) during July 2009.

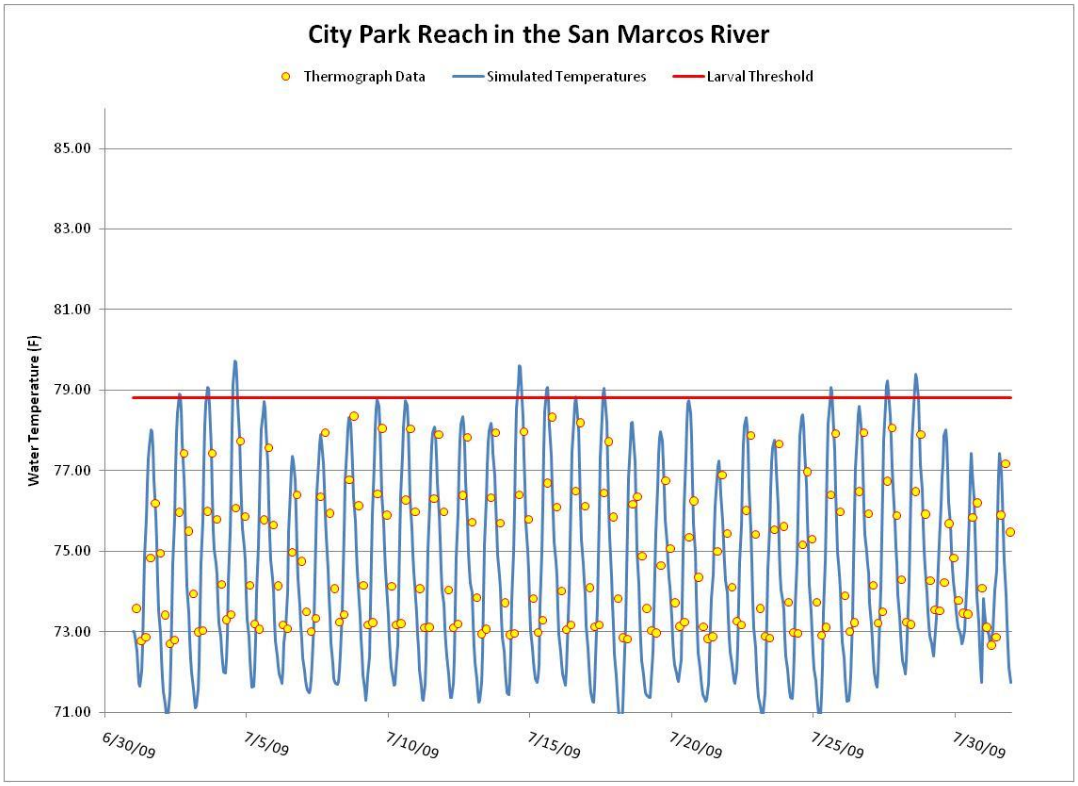


Figure 26. Simulated and observed water temperatures in City Park, San Marcos River during July 2009.

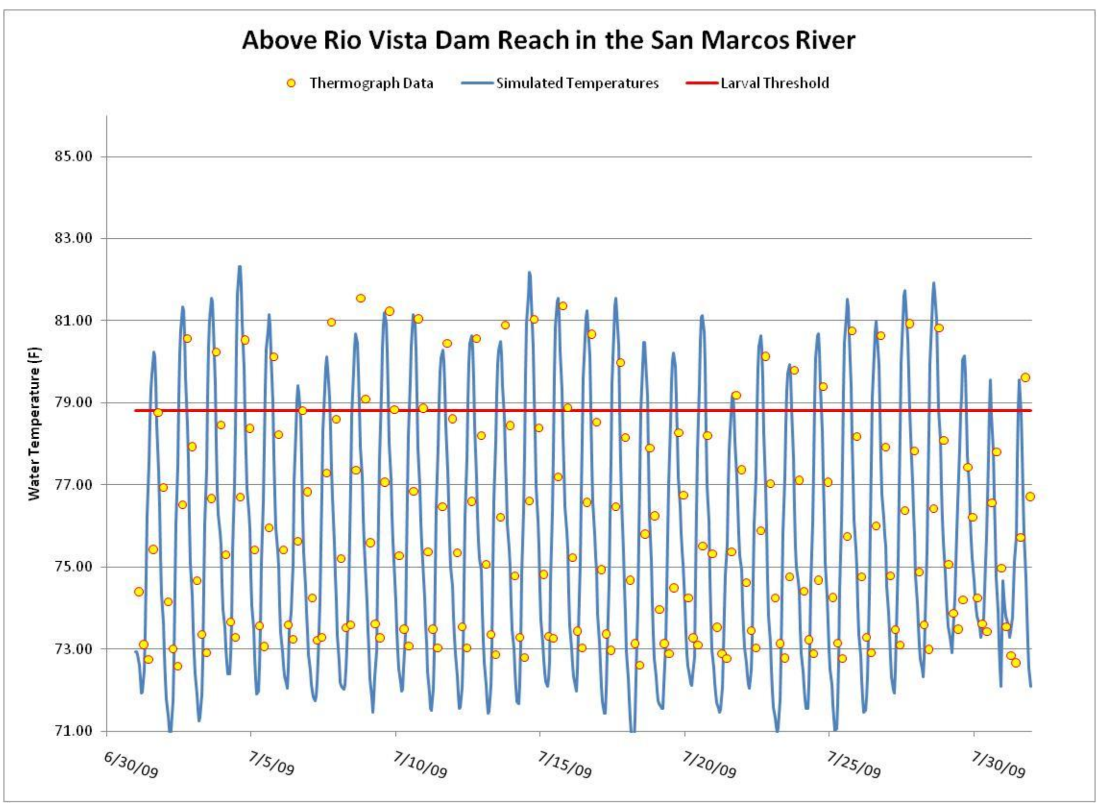


Figure 27. Simulated and observed water temperatures above Rio Vista Dam, San Marcos River during July 2009.

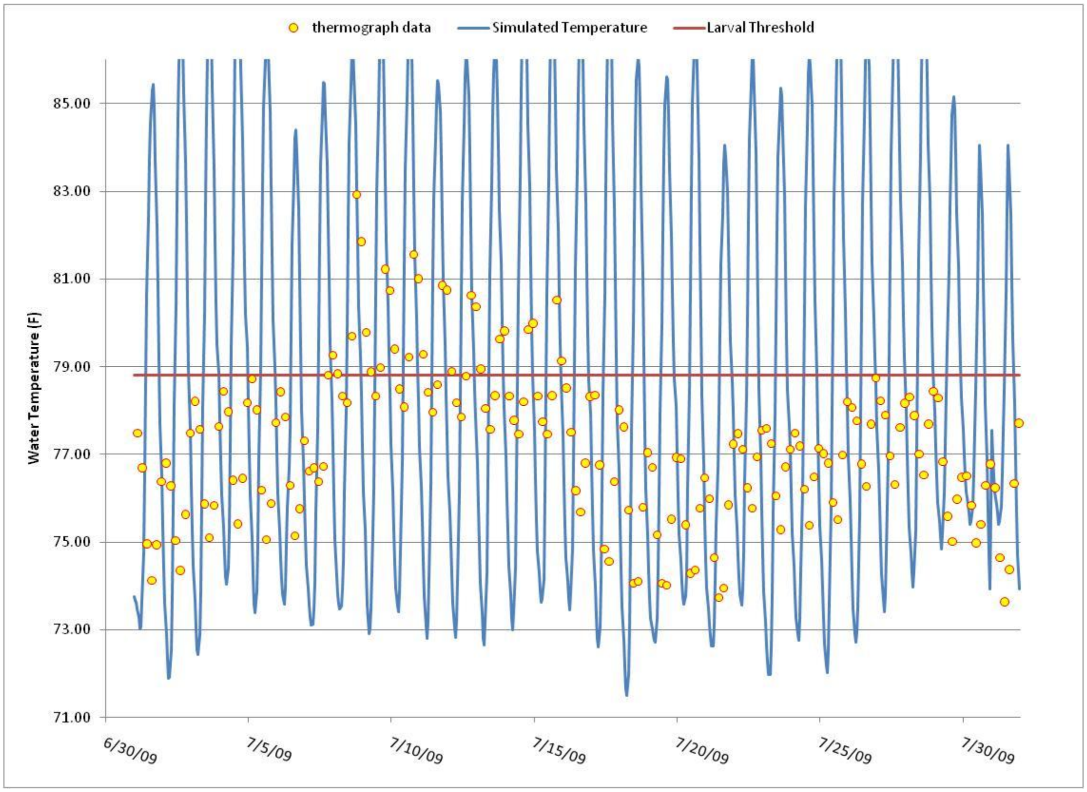


Figure 28. Simulated and observed water temperatures a Thompson Island natural channel, San Marcos River during July 2009.

Results and Discussion

San Marcos Physical Habitat Modeling

A total of 40,456 in water topography points were collected within ~ 5.5 miles of the San Marcos River from September 2009 – January 2010. An additional 36,163 topography points were added from Hays County, Texas contour maps to extend 6 feet of elevation outside the river's edge. This represents a significant improvement to the spatial resolution underlying all the hydraulic and habitat computational grids used in the assessments. Predicted wetted stream area within each modeled segment as a function of simulated discharge for the San Marcos River is provided in Table 14. Total wetted stream area ranged from 96,233 m^2 at 30cfs to 132,140 m^2 at 260 cfs.

Texas Wild Rice

The 2009 mapped TWR population within the San Marcos River consisted of 2,661.23 m^2 and was distributed from Spring Lake downstream to just below the Texas Parks and Wildlife Fish Hatchery. The river segment, Saltgrass through Sewell Park contained the greatest concentration TWR, comprising 825.25 m^2 of TWR. Approximately 90% of the TWR population was found to occur upstream of Cape's dam, totaling 2,380 m^2.

Simulated TWR Physical Habitat

Figures 29 to 31 provide a comparison of the combined suitability based on depth and velocity HSC for TWR for a range of discharge between 30 and 80 cfs for various sections of the San Marcos River. Plan view plots of the combined suitability predicted for TWR for each modeled section for each flow rate are provided in Appendix C. These results illustrate several key aspects. The highest predicted suitable habitat generally occurs somewhat away from the stream margins both at 45 and 80 cfs. These results suggest that potential high quality areas in these regions currently not occupied by TWR should be considered for planting or priorities for non-native vegetation removal as discussed below. The results also show that over the target flow regime ranges being considered for the San Marcos River there generally is not a large difference in the hydraulic suitability mosaic between 45 and 80 cfs. The low flow regime experienced during the summer of 2009 (~ 88 cfs) did not result in substantial loss of existing TWR stands based on field mapping. BioWest (2010b) did document reductions in aquatic vegetation within the San Marcos River that was attributed to physical disturbance associated with high recreational use. However, under the EARIP assumption of adequate recreational impact controls, the simulation results suggest the target flow regime being contemplated by the EARIP for the drought of record will provide adequate occupied areas in high quality habitat to sustain TWR populations as illustrated below.

Simulated TWR Optimal versus Suboptimal Physical Habitat

We evaluated simulated physical habitat to evaluate both 'optimal' TWR habitat where the combined suitability for depth and velocity was greater than 0.75 and suboptimal habitat ($\leq$ 0.75). The results for simulated TWR optimal and suboptimal area for the full range of simulated discharges are provided in Table 15. The simulated area of optimal TWR habitat increased until a flow rate of 120 cfs and then slowly decreased thereafter. Total predicted optimum TWR habitat area ranged from 21,709 m^2 at 30 cfs to 37,407 m^2 at 120 cfs. It is noted for these specific results that these areas of predicted TWR habitat may not be occupied by TWR.

The 2009 mapped TWR locations within simulated optimum habitat areas in the San Marcos River increased until a flow rate of 80 cfs and slowly decreased thereafter. The 2009 TWR mapped locations within predicted optimum habitat areas ranged from 1,246 m^2 at 30 cfs to 1,678 m^2 at 80 cfs. Greater depths (i.e., depths greater than 1m) associated with discharges higher than 80 cfs became the limiting factor for optimum TWR habitat areas. As noted previously, this is related to the depth HSC for TWR which rapidly declines after about 3 feet (i.e., 1 m). The 2009 mapped TWR locations found within suboptimum habitat areas displayed the reverse pattern of TWR found within optimum habitat areas by decreasing in area until 80 cfs and then steadily increasing with increased discharge. The percent of TWR optimal habitat as a function of stream surface area within the San Marcos River increased from 22.56% at 30 cfs to 32.83 % at 100 cfs and steadily decreased to 21.22 % at 260 cfs (Figure 32).

It is clear based on the existing physical habitat simulation results that existing stands of TWR occupy both optimal and suboptimal areas within the San Marcos River. This is both expected from previous modeling efforts and empirical studies across a wide array of species that have documented that habitat utilization in suboptimal areas is common in the face of inter-specific competition and habitat availability. We believe that the simulation results strongly suggest that expansion of TWR into areas of simulated unoccupied optimal areas that are 'stable' over a wide range of discharges are likely possible and should be evaluated within the EARIP adaptive management process.

Table 14. Predicted wetted stream area (m2) for each modeled segment of the San Marcos River under various discharges (cfs).

Discharge (cfs)	Clear Springs	Saltgrass through Sewell Park	Sewell Park to Snake Island	Snake Island to Rio Vista	Cheatham St to I35	I35 to Capes	Thompson Island part 1	Thompson Island part 2	After Mill Run Seg 1	After Mill Run Seg 2.1	After Mill Run Seg 2.2	Total
30	NA	4,305	15,600	16,582	8,643	7,922	8,658	5,607	11,660	10,473	6,784	**96,233**
45	NA	4,568	16,155	18,887	9,004	7,970	8,945	6,014	11,685	10,863	6,958	**101,049**
50	NA	4,638	16,255	19,549	9,089	8,004	9,017	6,204	11,711	11,027	7,072	**102,566**
55	857	4,696	16,351	19,549	10,414	8,026	9,094	6,166	11,737	10,609	7,237	**103,879**
60	873	4,701	16,447	19,949	10,414	8,046	9,169	6,401	11,763	10,788	7,299	**104,978**
70	1,102	5,008	16,592	20,716	10,599	8,119	9,282	6,567	11,846	11,437	7,424	**107,590**
80	1,199	5,105	16,723	21,457	10,748	8,236	9,400	6,720	11,883	11,485	7,561	**109,318**
90	1,200	5,216	16,832	22,004	10,884	8,353	9,496	6,872	11,963	11,951	7,670	**111,242**
100	1,313	5,395	16,940	22,435	11,074	8,415	9,638	7,156	12,059	12,244	7,768	**113,124**
120	1,372	5,654	17,119	23,107	11,352	8,635	10,011	7,664	12,222	12,743	7,907	**116,414**
140	1,559	5,757	17,236	23,668	11,660	8,784	10,358	7,902	12,343	13,586	8,000	**119,295**
160	1,694	5,846	17,327	24,206	11,847	8,943	10,616	8,740	12,435	14,419	8,046	**122,427**
180	1,737	5,927	17,398	24,470	12,156	9,280	10,782	9,013	12,546	15,313	8,071	**124,955**
200	1,889	6,001	17,444	24,649	12,432	9,466	10,929	9,216	12,682	15,760	8,084	**126,664**
220	2,031	6,072	17,449	24,688	12,850	9,603	11,079	9,437	12,725	16,431	8,084	**128,417**
240	2,135	6,151	17,471	24,766	13,207	9,764	11,313	9,656	12,805	17,103	8,084	**130,320**
260	2,195	6,193	17,478	24,805	13,606	9,870	11,438	9,864	12,867	17,935	8,084	**132,140**

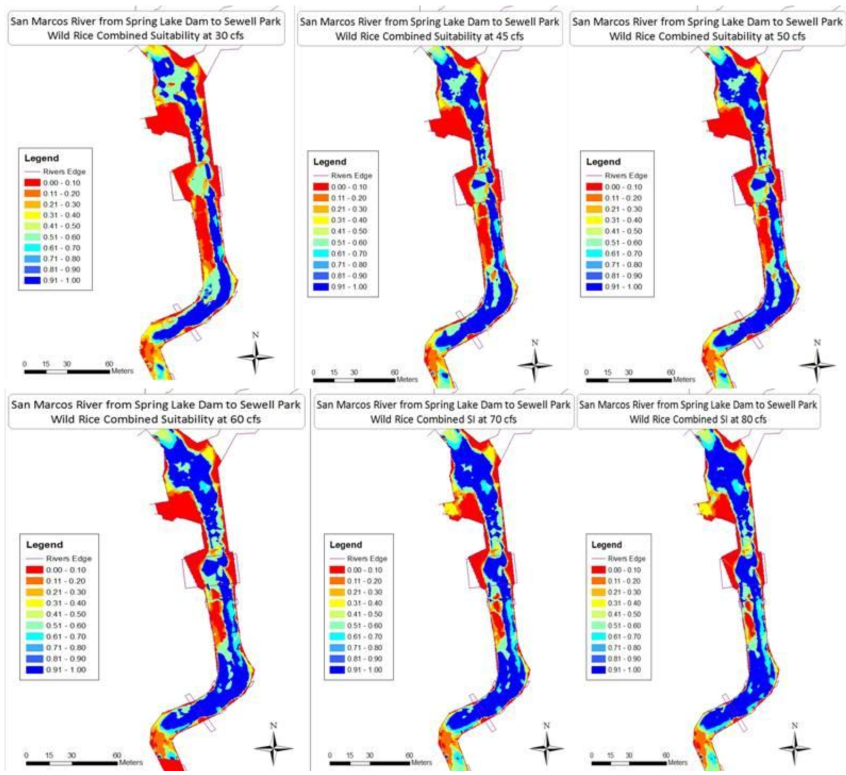


Figure 29. **Combined suitability for TWR physical habitat for a range of discharge within the Saltgrass to Sewell Park reach of the San Marcos River.**

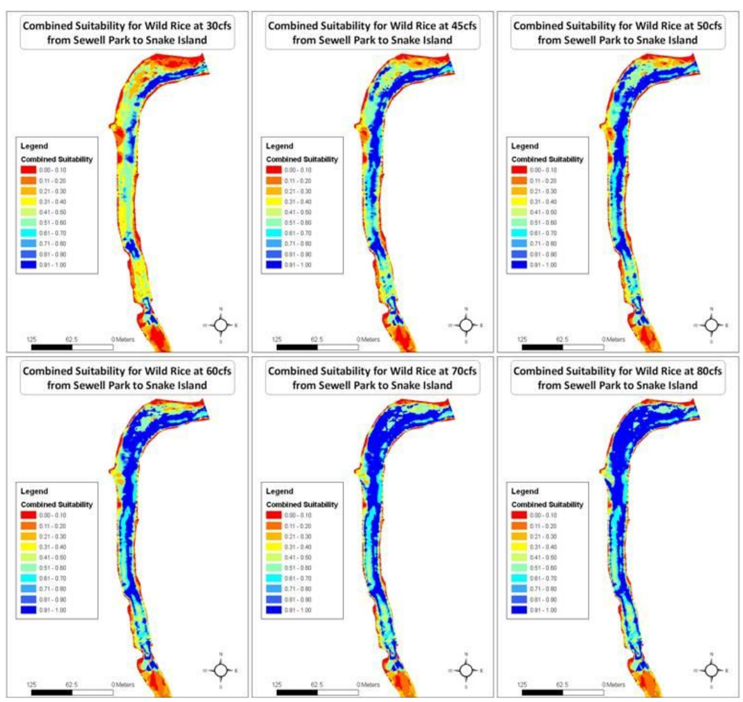


Figure 30. **Combined suitability for TWR physical habitat for a range of discharge within the Sewell Park to Snake Island reach of the San Marcos River.**

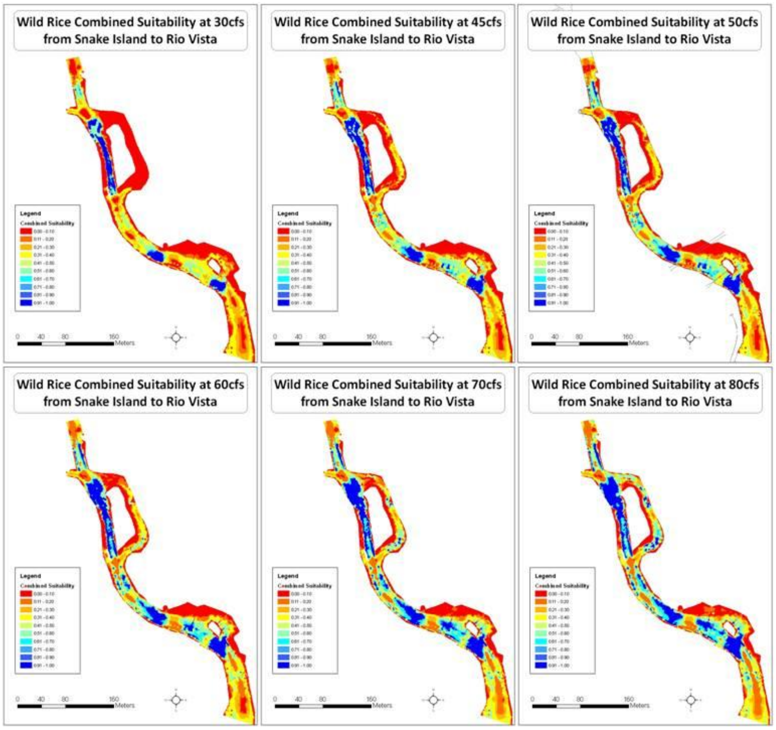


Figure 31. Combined suitability for TWR physical habitat for a range of discharge within the Snake Island to Rio Vista Dam reach of the San Marcos River.

Table 15. Predicted optimum TWR areas (m^2) [not necessarily occupied], 2009 mapped TWR predicted within optimum/suboptimum areas, additional areas with removal of H. verticillata and H. polysperma within TWR patches and a 2 meter buffer around TWR patches in the San Marcos River. Note that the sum of columns 3 and 4 is the total of occupied 2009 TWR habitat mapped by Texas State.

Discharge (cfs)	Optimum area (>75% suitable)	Optimum area (>75% suitable)	Suboptimum area (≤75% suitable)	*H. verticillata* *H. polysperma* Removal in TWR patches	2 m buffer TWR patches
30	21,709	1,246	1,486	594	779
45	26,785	1,518	1,224	1,134	1,292
50	29,087	1,596	1,146	1,269	1,452
55	29,182	1,603	1,134	1,345	1,527
60	31,049	1,630	1,113	1,423	1,585
70	33,667	1,675	1,068	1,499	1,673
80	34,730	1,678	1,057	1,548	1,748
90	36,274	1,667	1,087	1,564	1,793
100	37,142	1,635	1,100	1,572	1,827
120	37,407	1,542	1,199	1,219	1,795
140	36,957	1,428	1,308	1,345	1,722
160	36,077	1,288	1,451	1,278	1,663
180	35,366	1,144	1,592	1,212	1,614
200	33,294	980	1,760	1,074	1,515
220	31,875	781	1,954	958	1,371
240	30,226	615	2,121	840	1,201
260	28,043	482	2,250	741	1,083

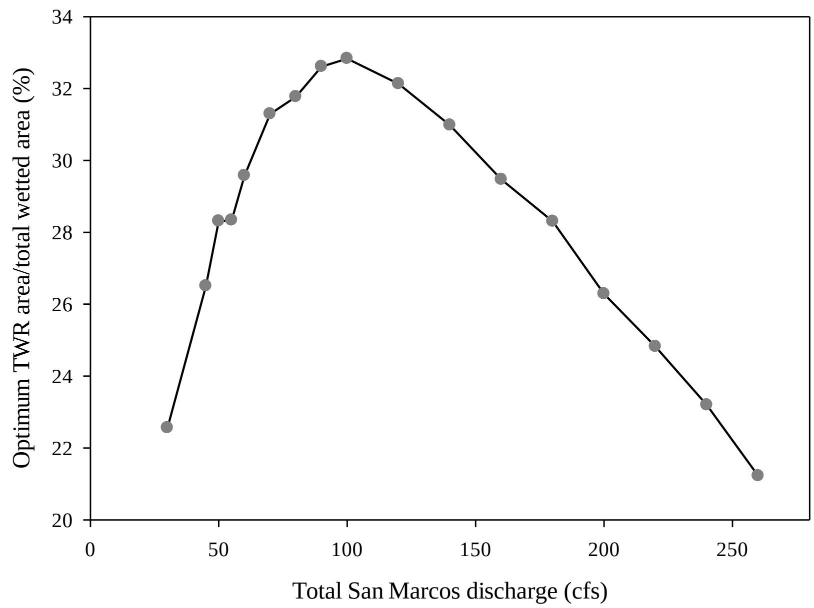


Figure 32. **Percent of total stream surface area (m2) predicted as optimum habitat for TWR under various discharges within San Marcos River.**

Predicted optimum TWR habitat area was generally greater upstream of Rio Vista than downstream (Figure 33). Only over lower flow ranges (i.e., < 50cfs) was more optimum TWR habitat area predicted to be downstream of Rio Vista. Predicted optimum TWR habitat area upstream of Rio Vista steadily increased from 8,131 m^2 at 30 cfs to 23,468 m^2 at 200 cfs and slowly decreased to 19,992 m^2 at 260 cfs. Downstream of Rio Vista, predicted optimum TWR habitat increased from 13,577 m^2 at 30 cfs to 16,093 m^2 at 90 cfs and declined at the higher simulated discharges.

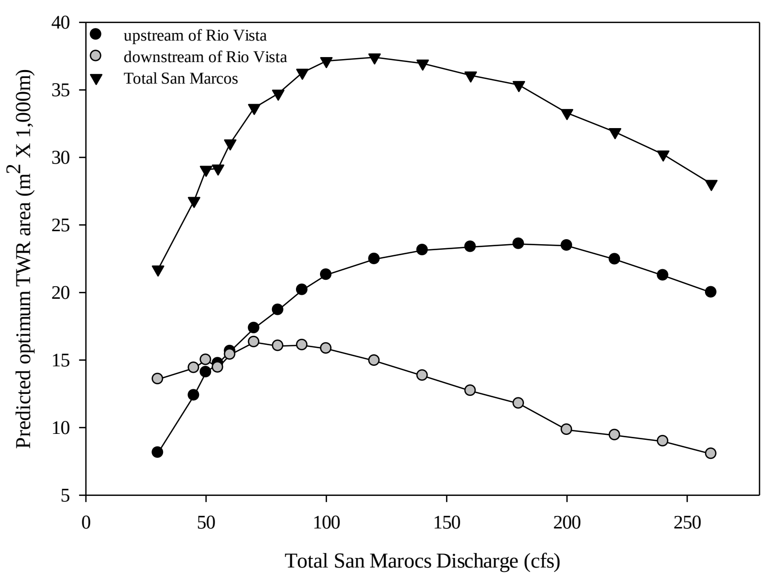


Figure 33. **Predicted optimum TWR habitat areas (m2 X 1000m) upstream of Rio Vista (black dots), downstream of Rio Vista (gray dots) and total San Marcos River (black triangles) under various discharges in the San Marcos River.**

Potential TWR expansion with removal of H. verticillata and H. polysperma

Figure 34 illustrates the potential addition of TWR habitat with the removal of *H. verticillata* and *H. polysperma* within predicted optimum areas of occupied TWR habitat and within a 2 m buffer around occupied optimal TWR areas. These data are also provided in Table 15. The removal of *H. verticillata* and *H. polysperma* within TWR patches and including a 2 meter buffer around TWR patches would provide over 1000 m^2 of additional optimum TWR habitat area over the entire flow range simulated. As was noted previously, the simulated optimal habitat for TWR over a range of discharges between 45 and 80 cfs strongly suggests that proactive planting and conservative non-native vegetation removal has a high potential for increasing existing TWR occupied area that would remain hydraulically suitable over the target flow regime discharges being considered by the EARIP.

Figure 35 provides an overlay of Table 15 on the example minimum target flow regime for the San Marcos River with benchmark flows indicated over various time intervals during the drought of record. These results illustrate that both occupied TWR in optimal habitat conditions and the potential increases in occupied areas with successful non-native vegetation removal are expected to provide adequate protection for TWR during the drought of record under the flow regimes being contemplated by the EARIP.

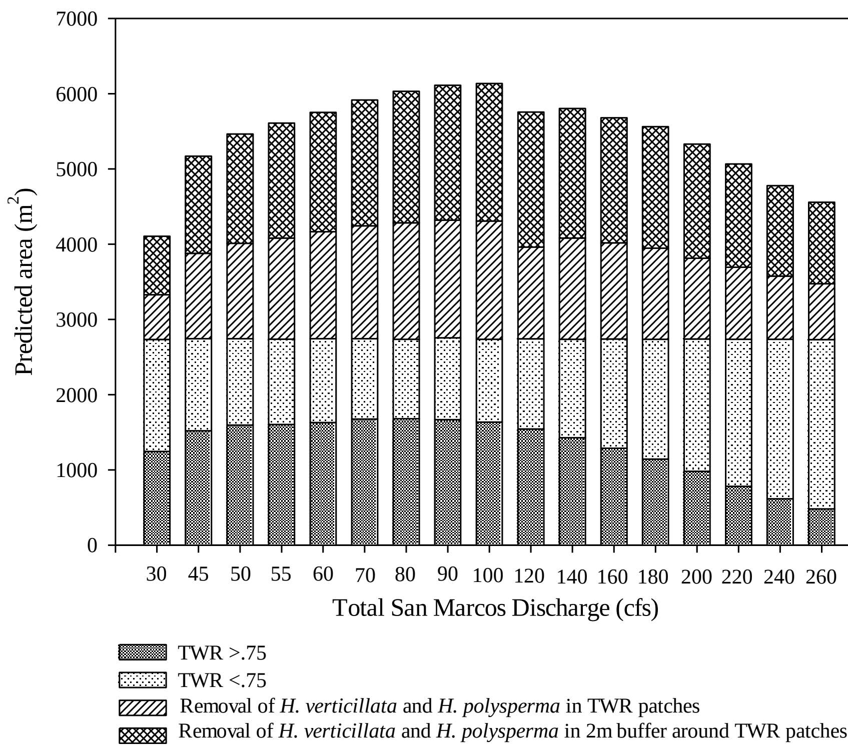
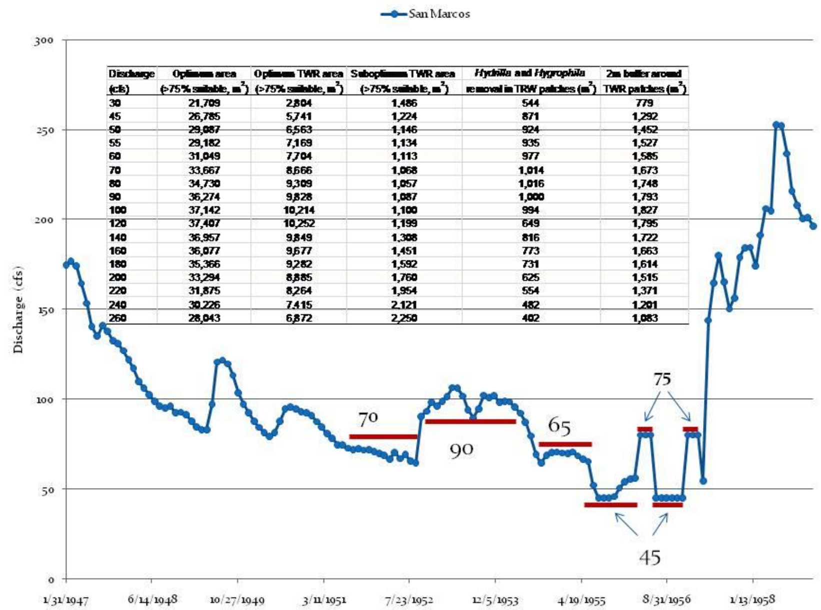


Figure 34. 2009 mapped TWR area within optimum/suboptimum habitat (m2) and predicted addition of optimum occupied TWR habitat with removal of H. verticillata and H. polysperma and areas within a 2 m buffer of occupied optimal TWR patches in the San Marcos River.



Discharge (cfs)	Optimum area (>75% suitable, m²)	Optimum TWR area (>75% suitable, m²)	Suboptimum TWR area (>75% suitable, m²)	*Hydrilla* and *Hygrophila* removal in TRW patches (m²)	2m buffer around TWR patches (m²)
30	21,709	2,804	1,486	544	779
45	26,785	5,741	1,224	871	1,292
50	29,087	6,563	1,146	924	1,452
55	29,182	7,169	1,134	935	1,527
60	31,049	7,704	1,113	977	1,585
70	33,667	8,666	1,068	1,014	1,673
80	34,730	9,309	1,057	1,016	1,748
90	36,274	9,828	1,087	1,000	1,793
100	37,142	10,214	1,100	994	1,827
120	37,407	10,252	1,199	649	1,795
140	36,957	9,849	1,308	816	1,722
160	36,077	9,677	1,451	773	1,663
180	35,366	9,282	1,592	731	1,614
200	33,294	8,885	1,760	625	1,515
220	31,875	8,264	1,954	554	1,371
240	30,226	7,415	2,121	482	1,201
260	28,043	6,872	2,250	402	1,083

Figure 35. **Example of target minimum flow regime during the drought of record with TWR habitat simulation results.**

Fountain Darters

The analysis of darter habitat was broken down into two components. The first analysis considers only physical habitat based on depth, velocity, and vegetation. The second analysis considers the potential impacts associated with water temperatures.

Simulated Fountain Darter Physical Habitat

Figures 36 through 38 provide examples of the combined suitability of darter habitat over ranges of discharges for sections of the San Marcos River. Plan view plots of the combined suitability for darters at each simulated discharge for each modeled section of the San Marcos River are provided in Appendix D.

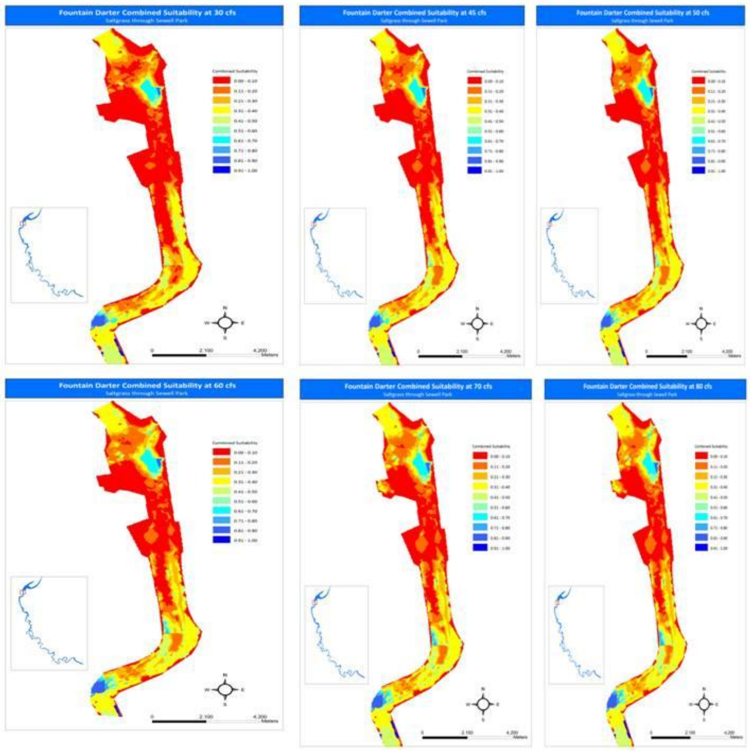


Figure 36. **Combined suitability of darter habitat over a range of discharges in the Saltgrass to Sewell Park reach of the San Marcos River.**

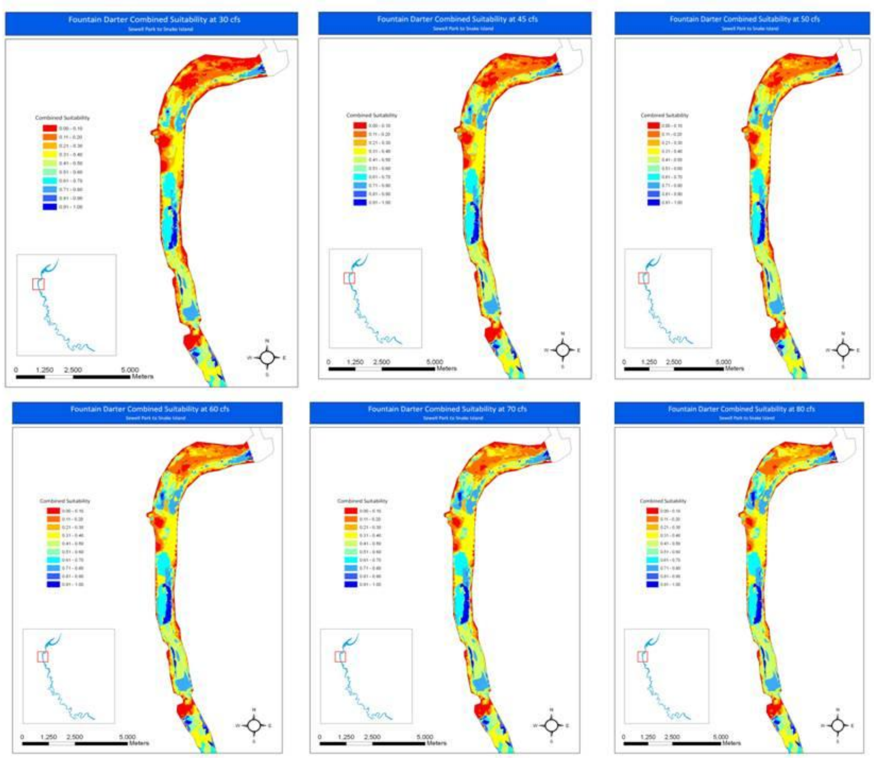


Figure 37. **Combined suitability of darter habitat over a range of discharges in the Sewell Park to Rio Vista reach of the San Marcos River.**

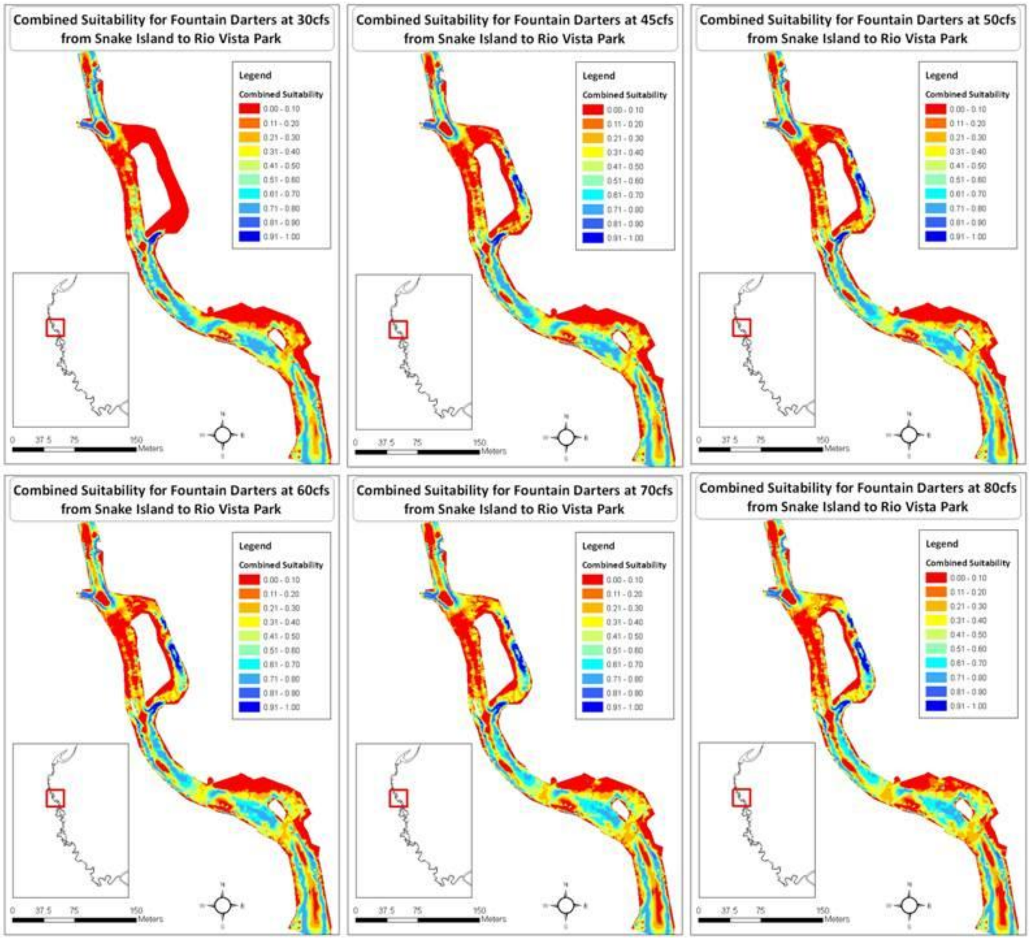


Figure 38. **Combined suitability of darter habitat over a range of discharges in the Snake Island to Rio Vista Dam reach of the San Marcos River.**

These results illustrate that in general the combined suitability of darter habitat show incremental increases as the discharge increases and that the spatial mosaic remains relatively constant. This is in part related to integration of vegetation in the calculation of the combined suitability which remains fixed over all ranges of simulated discharges. Potential changes in vegetation as a function of flow regime within the San Marcos River were not considered in these analyses. The simulations of physical habitat therefore, basically show the influence of changes in depth and velocity with changes in discharge.

Darter physical habitat within Spring Lake was estimated at 33,862 m^2 and was considered to remain constant for all simulated discharges (see Methods). The area for Spring Lake was not included in the riverine reach totals shown below since it was a constant. Totals for predicted weighted useable areas (WUA) for fountain darters are provided in Table 16. Fountain darter WUA increased with increasing discharge in the San Marcos River and ranged from 35,841 m^2 at 30 cfs to 54,735 m^2 at 260 cfs. The percent of WUA as a percent of total stream area increased with discharge from 23.33% at 30 cfs to 35.63% at 260 cfs (Figure 39). Similar to TWR, fountain darter WUA was generally greater upstream of Rio Vista dam than downstream (Figure 40). Only at lower flows (i.e., < 90cfs) was more fountain darter WUA predicted downstream of Rio Vista. Fountain darter WUA upstream of Rio Vista increased from

15,932 m^2 at 30 cfs to 29,721 m^2 at 260 cfs and increased from 19,909 m^2 at 30 cfs to 25,014 m^2 at 260 cfs downstream of Rio Vista.

Table 16. Predicted fountain darter WUA (m2) upstream of Rio Vista, downstream of Rio Vista, and total for the San Marcos River for all simulated discharges.

Discharge (cfs)	FD WUA upstream of Rio Vista	FD WUA downstream of Rio Vista	FD WUA total San Marcos
30	15,932	19,909	35,841
45	17,507	20,239	37,746
50	17,901	20,263	38,164
55	18,319	20,436	38,755
60	18,636	20,388	39,025
70	19,516	20,504	40,020
80	20,248	20,536	40,784
90	20,911	20,663	41,574
100	21,611	20,891	42,502
120	22,991	21,174	44,165
140	24,357	21,535	45,891
160	25,592	22,110	47,702
180	26,624	22,614	49,237
200	27,654	22,375	50,029
220	28,545	23,171	51,716
240	29,320	24,450	53,770
260	29,721	25,014	54,735

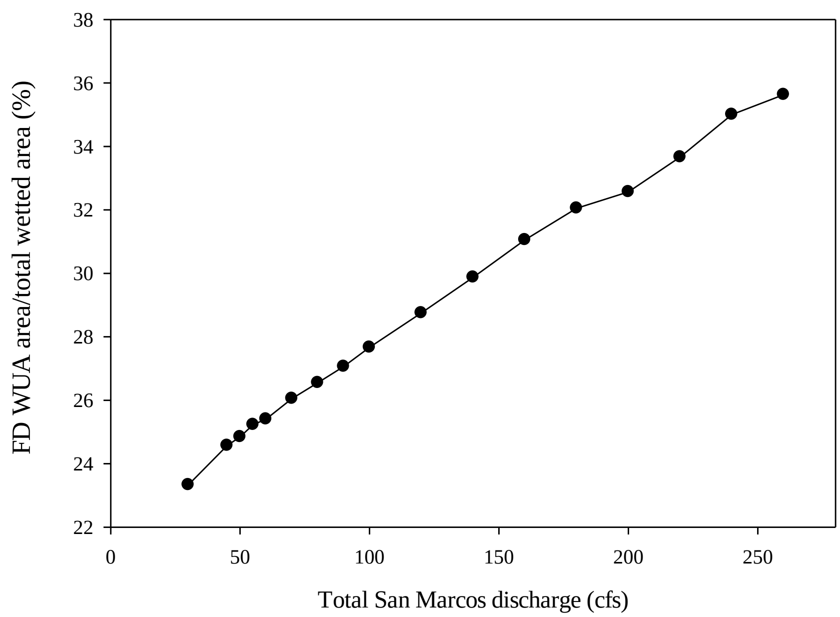


Figure 39. Percentage of total wetted area predicted as weighted usable area (WUA) for fountain darters under various discharges within San Marcos River.

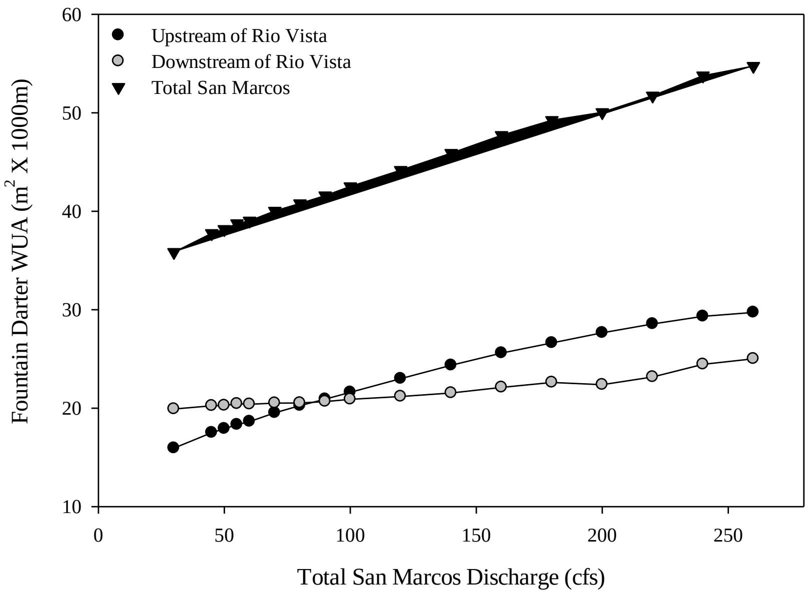


Figure 40. **Relationship between the amount of fountain darter WUA (m2 X 1000) upstream of Rio Vista (black dots), downstream of Rio Vista (gray dots), and total San Marcos River under various discharges.**

The results provided above indicate that over the flow regime range of discharges being considered by EARIP, darter physical habitat reductions between 45 and 80 cfs cfs results in about a 10 percent reduction (i.e., 59 versus 68 as a percent of the simulated maximum habitat at the highest flow) for habitat above Rio Vista or for the total within the San Marcos River under the assumption of fixed vegetation composition and spatial distribution as mapped in 2009. As noted previously, aquatic vegetation was negatively impacted in some reaches due to recreation (BioWest 2010b). This underscores the necessity to implement adequate control measures for protection of the aquatic vegetation community, not just TWR, to reduce potential secondary impacts on darters. It also highlights the importance of non-native fish control (e.g., suckermouth catfish, tilapia) which have the capacity to also alter the vegetation community. However, under the assumption that the EARIP mitigation measures are successful, we believe the simulation results support that the proposed target flow regime magnitudes being considered by the EARIP will maintain sufficient physical habitat for darters within the San Marcos River. Potential limiting conditions for temperature are considered below.

Implications of Temperature on Fountain Darters

The calibrated Qual2e model was used to simulate a range of discharge within the San Marcos River on an hourly basis. As noted in the Methods Section, July 15th was chosen as a representative day given the similarity of results over the entire month of July. The analysis focuses on the assessment of thermal impacts on darter life history requirements associated with three thresholds. Thermal death is assumed to occur if water temperatures reach 94.6 F, egg production stops at 86 F, and increased larval mortalities start at 78.8 F. We recognize that translation of laboratory values to field conditions are imperfect and successful darter reproduction and recruitment has been observed at measured water temperatures in the high 80 F range within the Comal River (BioWest 2010a). However, we utilize these values as consistent metrics to evaluate the water temperature simulations in light of darter life history requirements.

Figures 41 to 45 show a comparison between the hourly simulated temperatures for several reaches within the San Marcos River at 45 and 80 cfs.

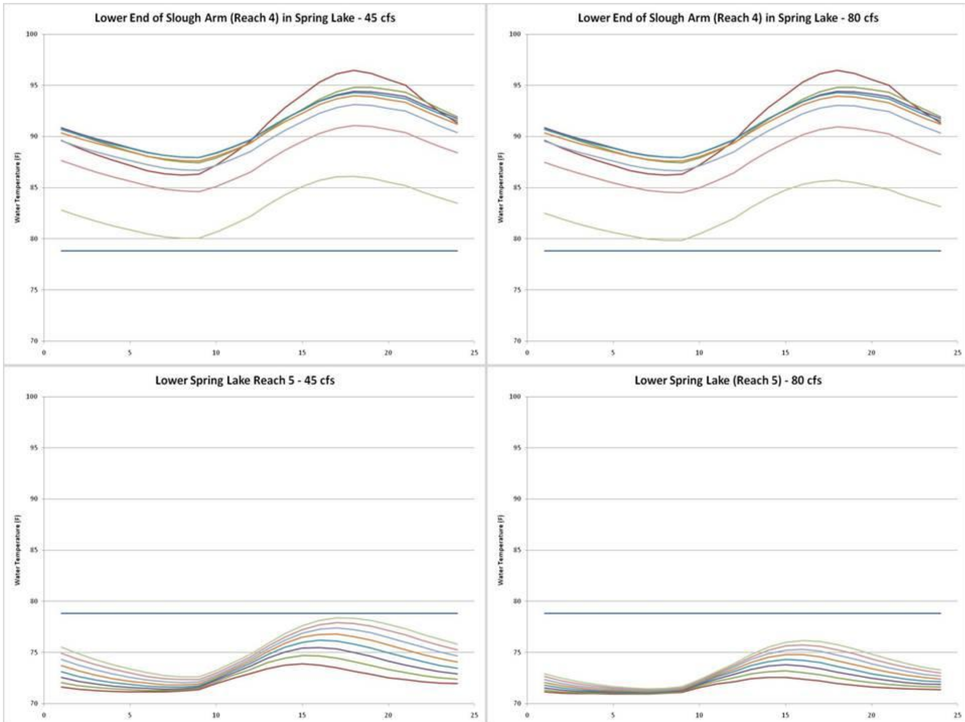


Figure 41. **Simulated hourly temperature profiles in Reach 4 and 5 of the San Marcos River at 45 and 80 cfs.**

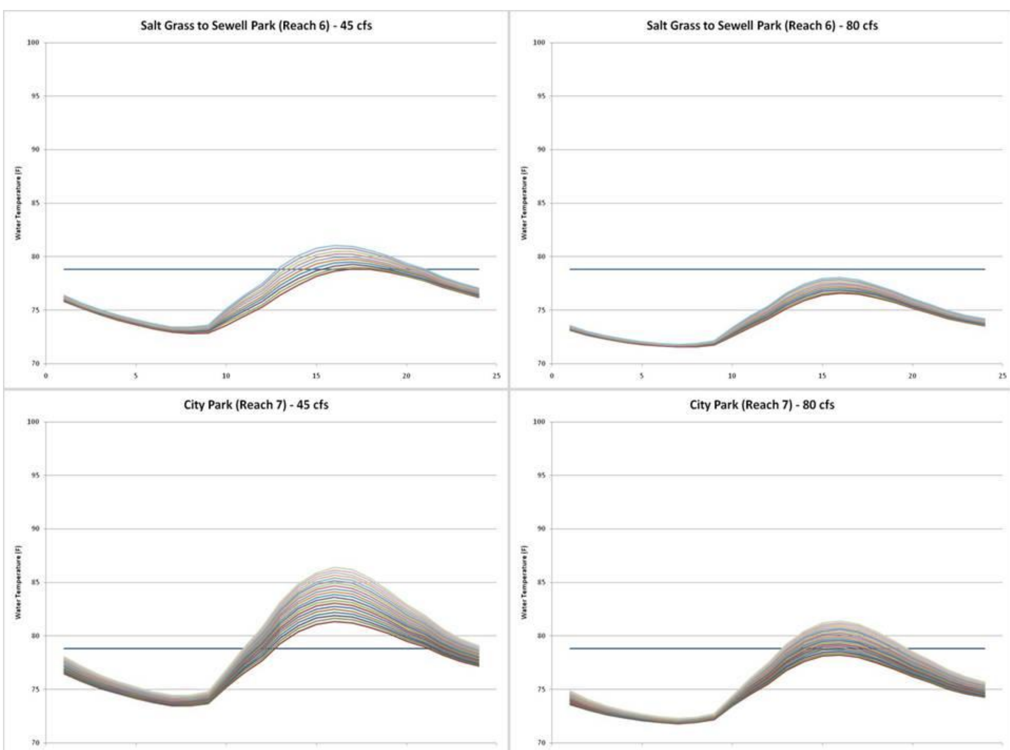


Figure 42. **Simulated hourly temperature profiles in Reach 6 and 7 of the San Marcos River at 45 and 80 cfs.**

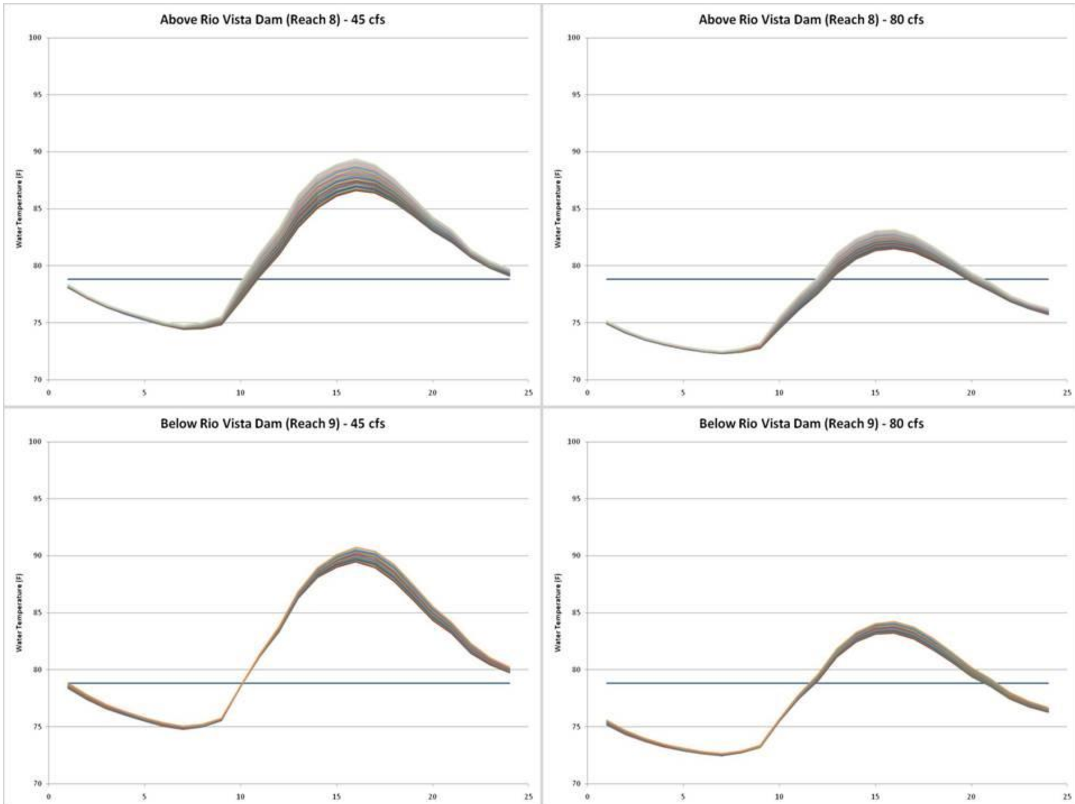


Figure 43. **Simulated hourly temperature profiles in Reach 8 and 9 of the San Marcos River at 45 and 80 cfs.**

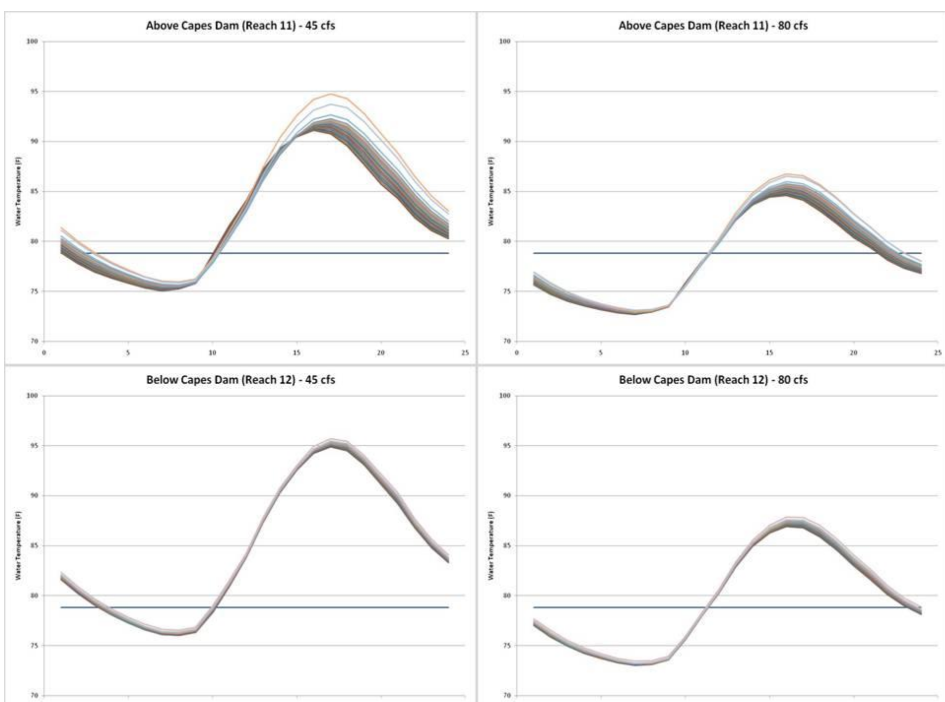


Figure 44. **Simulated hourly temperature profiles in Reach 11 and 12 of the San Marcos River at 45 and 80 cfs.**

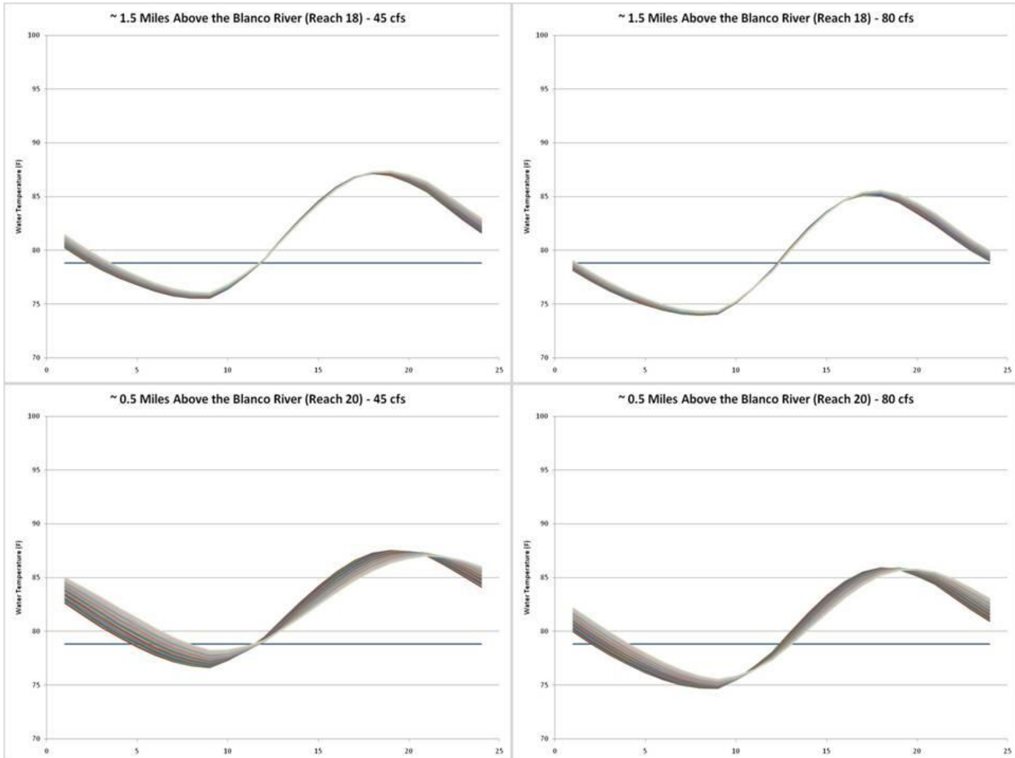


Figure 45. Simulated hourly temperature profiles in Reach 18 and 20 of the San Marcos River at 45 and 80 cfs.

The simulation results show that the Slough Arm in Spring Lake (Figure 41) will be thermally adverse to darters. We believe that this area will be behaviorally avoided by darters and is consistent with observations during later summer of 2009 when flows in this section were very low. The main body of Spring Lake (Reaches 1 and 5 – Figure 42) show that over the flow regime range being evaluated that no thermal limitations are anticipated for this part of the system at the higher discharge range (~ 80 cfs) and the empirical thermograph data supports these conclusions (see Figure 25).

As would be expected from the field measurements shown in Figures 26 through 28 taken in July 2009, the simulated maximum daily temperatures show a steady increase in the downstream direction below Spring Lake in the San Marcos River. At the upper range of discharges (80 cfs), the longitudinal thermal profile indicates that the threshold for increased larval mortality is exceeded for part of the day for slightly longer periods as one moves farther downstream from Spring Lake. However, at this flow rate, the simulations suggest that temperatures are not expected to reach the limiting temperature for cessation of egg production (86 F) and therefore we believe that darter reproduction and recruitment potential is expected through most of the system even during the summer period. We note that peak darter reproduction typically occurs during the spring period when ambient air temperatures are somewhat lower. The ambient air temperatures during the spring period in 2009 were approximately 75 F and simulations show that the longitudinal profile of maximum daily water temperatures remains below the larval threshold value over most sections of the San Marcos below Spring Lake and when exceeded, for a reduced number of hours during the day.

The simulations at 45 cfs indicate that Spring Lake proper remains well within preferred darter temperature ranges and the Slough Arm as expected is too hot for suitable darter habitat. Temperatures above the darter larval threshold move progressively upstream and for more hours of the day as would be expected from the reduction in the thermal mass of water at this flow rate compared to 80 cfs. The simulations suggest that thermal conditions suitable for darter persistence with some reproduction and recruitment potential would remain within the San Marcos upstream of Rio Vista Dam even during the summer period, albeit at reduced rates compared to the spring peak reproductive period (or late fall and winter due to reduced ambient air temperatures). We believe sections of the San Marcos River below Rio Vista would potentially have conditions that would likely inhibit any substantial reproduction or recruitment during the summer period at the high ambient air temperatures exhibited during the summer of 2009 but would still permit darter populations to persist. Lower fall, winter, and spring ambient temperatures would be expected to increase the areas with suitable water temperature regimes to sustain darter reproduction and larval survival at the 45 cfs flow range. At this lower flow rate during fall, winter, and spring, suitable ranges of temperatures extend below Rio Vista Dam to the sections below the San Marcos wastewater treatment plant.

Comal River

A total of 130,065 topography points were used to model ~ 3.2 miles of the Comal River. In water topography points were collected from January 2010 – April 2010 and provided a relatively high spatial density of data for use in constructing the hydraulic and habitat modeling grids. Mean monthly discharge during this period ranged from 320 to 380 cfs. As would be expected the simulated total stream surface area within each modeled segment increased with increasing discharge (see Table 18). Total stream area ranged from 72,051 m^2 at 30 cfs to 78,200 m^2 at 300 cfs and reflects the confined nature of the channel.

Fountain Darters

The analysis of darter habitat was broken down into two components. The first analysis considers only physical habitat based on depth, velocity, and vegetation. The second analysis considers the potential impacts associated with temperatures.

Simulated Fountain Darter Physical Habitat in Landa Lake

As noted in the Methods Section, darter physical habitat within Landa Lake was based on the relationship between total Comal discharge and the associated water surface elevation that maintained wetted polygon areas for substrate and vegetation. The relationship between total Landa Lake darter habitat and the ranges of discharges being evaluated by the EARIP are provided in Table 17.

Table 17. Darter habitat in Landa Lake as a function of discharge.

Comal Discharge (cfs)	Dater Habitat (m2)
30	10,509
45	11,161
50	11,180
60	11,377
70	11,827
80	12,120

As flows are reduced, increasing areas at the north end of Landa Lake become progressively exposed due to lake topography. We anticipate that these areas in upper Landa Lake will still benefit from increased flow rates (i.e., 30 to 80 cfs) from a physical habitat perspective although the primary benefit being improved water temperatures in lower Landa Lake. We assume that most of the vascular aquatic vegetation would be lost in the very upper extant of Landa Lake, although some level of rapid algae and bryophyte growth would be expected in response to the wetting as discharges increased. Although these vegetation types can be highly utilized by darters (Biowest 2010a,b), thermal conditions are likely to preclude their utilization by darters over the lower flow regimes during the summer period. Conversely, we postulate that these areas would be utilized during late fall, winter, and early spring given the lower ambient air temperatures and therefore lower water temperatures.

The reduced area of useable habitat for darters with decreasing discharge in Landa Lake represents a compression of the available habitat for the overall aquatic community. This has the potential to increase competition for food resources as well as higher predation rates but the overall magnitude of these potential impacts remains unknown at this time. The fact that darters have persisted throughout the system over multiple low flow episodes over the past two decades suggests that this may not be a limiting factor over the flow regimes being considered by the EARIP. However, control of non-native predatory fish species should be considered an important element of the EARIP mitigation measures to reduce the uncertainty associated with increased predation risk. We believe that these species can effectively be controlled through selective sampling methods as anticipated by the proposed EARIP mitigation measures.

The reduced area of darter habitat in Landa Lake in conjunction with increased temperatures (see below) also has the potential to increase gill parasite infection rates, which in turn, may result in increased impacts on darter populations. Monitoring data on parasites suggest that at lower flows and high temperatures that increased darter infection rates can occur but the overall implications on darter population dynamics remains speculative. Pilot level parasite control efforts through selective harvest of snails (intermediate host) conducted during the fall of 2010 showed promising results (Oborny, personal communication). The degree to which full scale control can effectively be undertaken however, remains unknown and should be one of the focus areas under the anticipated adaptive management actions being contemplated by the EARIP.

Table 18. Predicted stream surface area (m^2) for each modeled segment of the Comal River under various discharges (cfs).

Total Discharge (cfs)	channel Flow Splits (cfs)	Top of old channel	U0C2	UCO3	UOC4	BOC1	BOC2	BOC4	BOC5	Upper new channel	Wurstfest to toobchute	TOTAL
30	**20/10**	2,556	2,072	885	1,054	6,535	9,196	11,493	4,222	14,534	19,504	**72,051**
45		-	-	-	-	-	-	-	-	14,588	19,623	-
50		-	-	-	-	-	-	-	-	14,594	19,645	-
55		-	-	-	-	-	-	-	-	14,642	19,661	-
60	**30/30**	2,667	2,121	911	1,078	7,130	9,460	11,502	4,763	14,645	19,686	**73,963**
70	**35/35**	2,715	2,251	937	1,081	7,130	9,462	11,507	4,907	14,650	19,737	**74,377**
80	**40/40**	2,754	2,291	964	1,087	7,139	9,464	11,511	5,063	14,653	19,779	**74,705**
90	**45/45**	2,803	2,317	986	1,091	7,087	9,464	11,515	5,290	14,658	19,833	**75,044**
100	**50/50**	2,853	2,347	999	1,127	7,139	9,465	11,520	5,564	14,673	19,880	**75,567**
110	**55/55**	2,891	2,378	1,013	1,142	7,139	9,467	11,525	5,775	14,690	19,930	**75,950**
120	**60/60**	2,933	2,409	1,037	1,162	7,139	9,468	11,530	6,029	14,707	19,980	**76,394**
150	**60/90**	2,933	2,409	1,037	1,162	7,139	9,468	11,530	6,029	14,740	20,109	**76,556**
175	**60/115**	2,933	2,409	1,037	1,162	7,139	9,468	11,530	6,029	14,792	20,299	**76,798**
200	**60/140**	2,933	2,409	1,037	1,162	7,139	9,468	11,530	6,029	14,879	20,488	**77,074**
225	**60/165**	2,933	2,409	1,037	1,162	7,139	9,468	11,530	6,029	14,957	20,702	**77,366**
250	**60/190**	2,933	2,409	1,037	1,162	7,139	9,468	11,530	6,029	15,117	20,910	**77,734**
275	**60/215**	2,933	2,409	1,037	1,162	7,139	9,468	11,530	6,029	15,118	21,097	**77,922**
300	**60/240**	2,933	2,409	1,037	1,162	7,139	9,468	11,530	6,029	15,188	21,305	**78,200**

Simulated Fountain Darter Physical Habitat in Riverine Sections

Figures 46 and 47 provide examples of the combined suitability of darter habitat over ranges of discharges for the new and old channels of the Comal River. Plan view plots of the combined suitability for darters over all simulated discharges for each modeled section for the Comal are provided in Appendix D.

As noted previously, simulated darter habitat is closely tied to the underlying vegetation polygons and therefore the differences in the results at specific locations shown in Figures 46 and 47 primarily reflect changes in the depth and velocity with changes in discharge. The results also underscore the large differences in available darter habitat in the old and new. The presence of large areas of aquatic vegetation within the old channel and suitable ranges of depth and velocity over the target flow regimes being considered provide a large amount of available darter physical habitat. In contrast, darter physical habitat within the new channel is controlled by both the distribution of aquatic vegetation as well as velocities. The confined nature of the new channel results in rapid increases in the velocity as discharges increase. It is not surprising that velocity becomes limiting to darters as discharges increase and this reach is also susceptible vegetation scour which in turn affects availability of suitable darter habitat (BioWest 2010a).

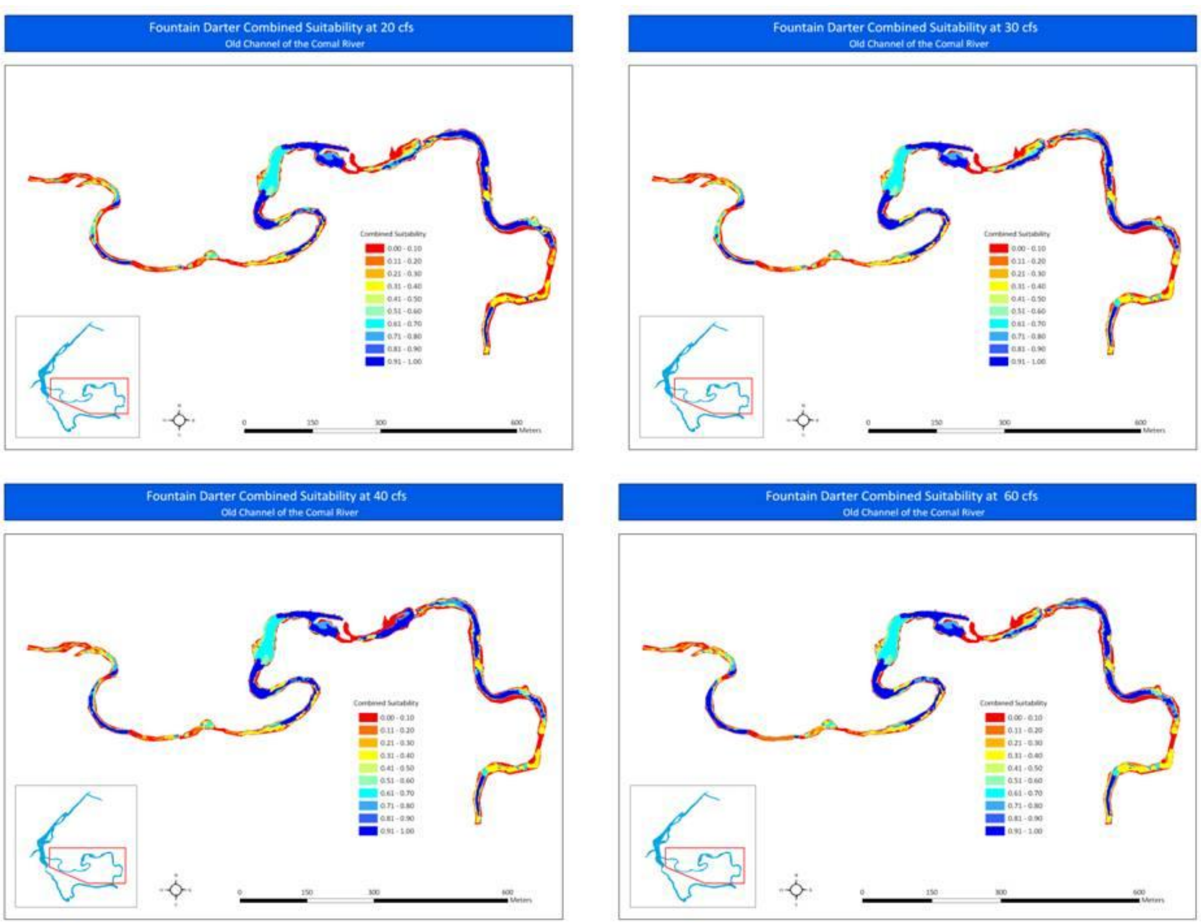


Figure 46. **Combined suitability of darter habitat over a range of discharges in the old channel reach of the Comal River.**

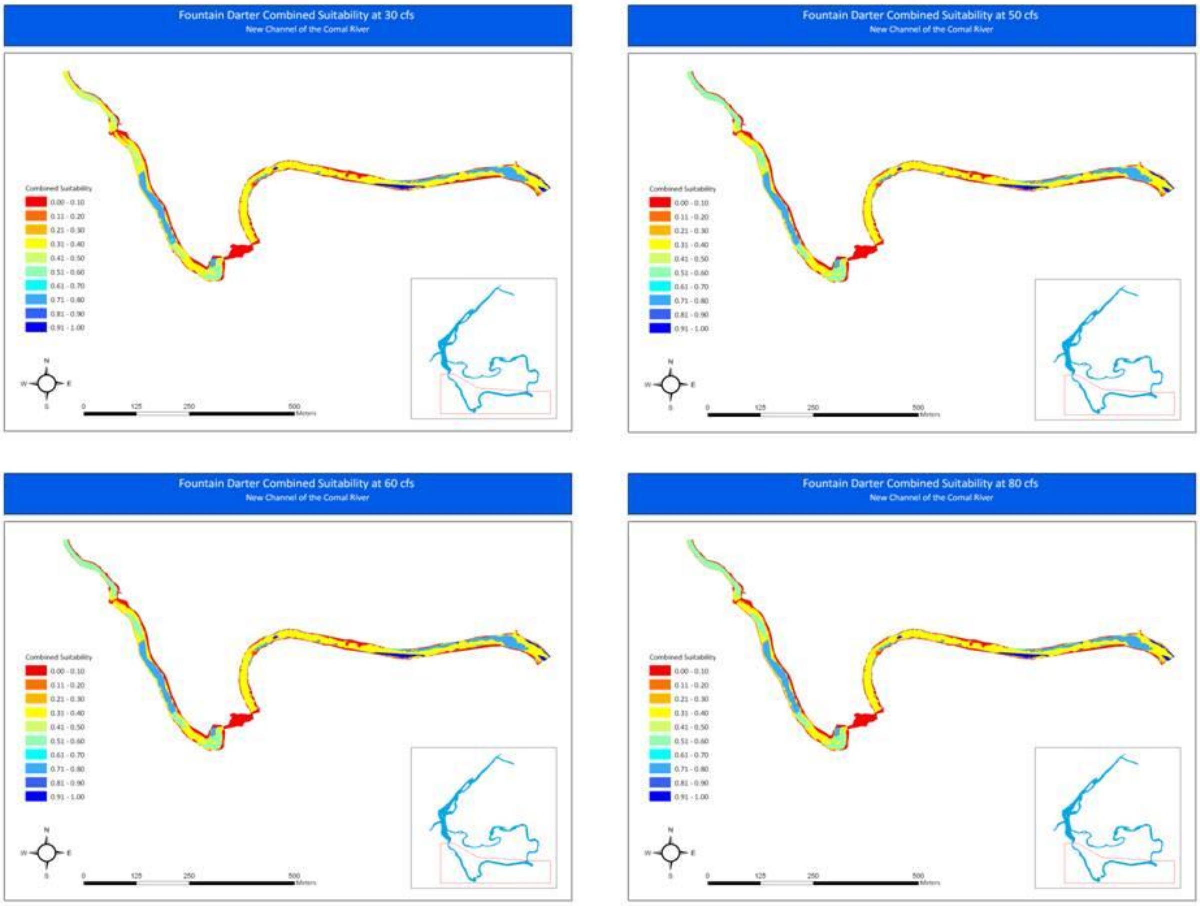


Figure 47. **Combined suitability of darter habitat over a range of discharges in the new channel reach of the Comal River.**

The predicted weighted useable areas (WUA) for fountain darters in the Comal River are provided in Table 20. Fountain darter WUA generally increased with increasing discharge in the Comal River and ranged from 18,471 m^2 at 10 cfs to 40,069 m^2 at 225 cfs. Fountain darter WUA was estimated to be greater in the old channel than the new channel of the Comal River (Figure 48) and is consistent with previous modeling efforts (e.g., Hardy et al., 1998). Fountain darter WUA in the old channel increased from 18,471 m^2 at 10 cfs (i.e., total discharge for the entire Comal River) and leveled off around 24,287 m^2 at 120 cfs. Fountain darter WUA in the new channel slightly increased from 15,122 m^2 at 30 cfs to 15,782 m^2 at 225 cfs. The lower amount of simulated habitat in the new channel is a function of reduced aquatic vegetation below the power plant as well as increased velocities at higher discharges. The percentage of total surface area predicted as weighted usable area for darters ranged from 48% to 52% within the Comal River (Figure 49). The relatively small change is to be expected given the confined nature of the channel.

Table 19. Predicted fountain darter WUA (m2) for the old channel and new channels of the Comal River under various discharges.

Discharge (cfs)	Darter Habitat (square meters)								
Old Channnel	BOC1	BOC2	BOC4	BOC5	UOC2	UOC3	UOC4	Top of Channel	Old Channel Total
10	3,476	6,142	5,234	1,476	883	172	311	777	18,471
20	3,821	6,224	5,903	1,544	1,103	185	318	833	19,931
30	4,419	6,448	6,763	1,658	1,148	198	326	879	21,837
40	4,416	6,449	6,896	1,871	1,509	210	336	908	22,595
45	4,409	6,450	7,109	1,954	1,588	213	338	924	22,984
50	4,402	6,451	7,220	2,039	1,649	213	381	935	23,291
55	4,389	6,453	7,660	2,127	1,720	215	389	949	23,902
60	4,377	6,455	7,888	2,217	1,776	217	400	956	24,287

Discharge (cfs)		Darter Habitat (square meters)		
Total Comal River	New Channel	Upper New Channel	Lower New Channel	New Channel Total
30	10	8,403	6,719	15,122
45	23	8,467	6,773	15,241
50	25	8,481	6,780	15,261
55	28	8,492	6,781	15,273
60	30	8,505	6,785	15,291
70	35	8,532	6,802	15,334
80	40	8,554	6,811	15,365
90	45	8,580	6,820	15,400
100	50	8,603	6,831	15,434
125	62	8,657	6,846	15,503
150	75	8,706	6,861	15,566
175	95	8,774	6,880	15,654
200	120	8,843	6,896	15,739
225	145	8,884	6,898	15,782
250	170	8,917	6,860	15,777
275	195	8,917	6,810	15,728
300	220	8,925	6,719	15,644

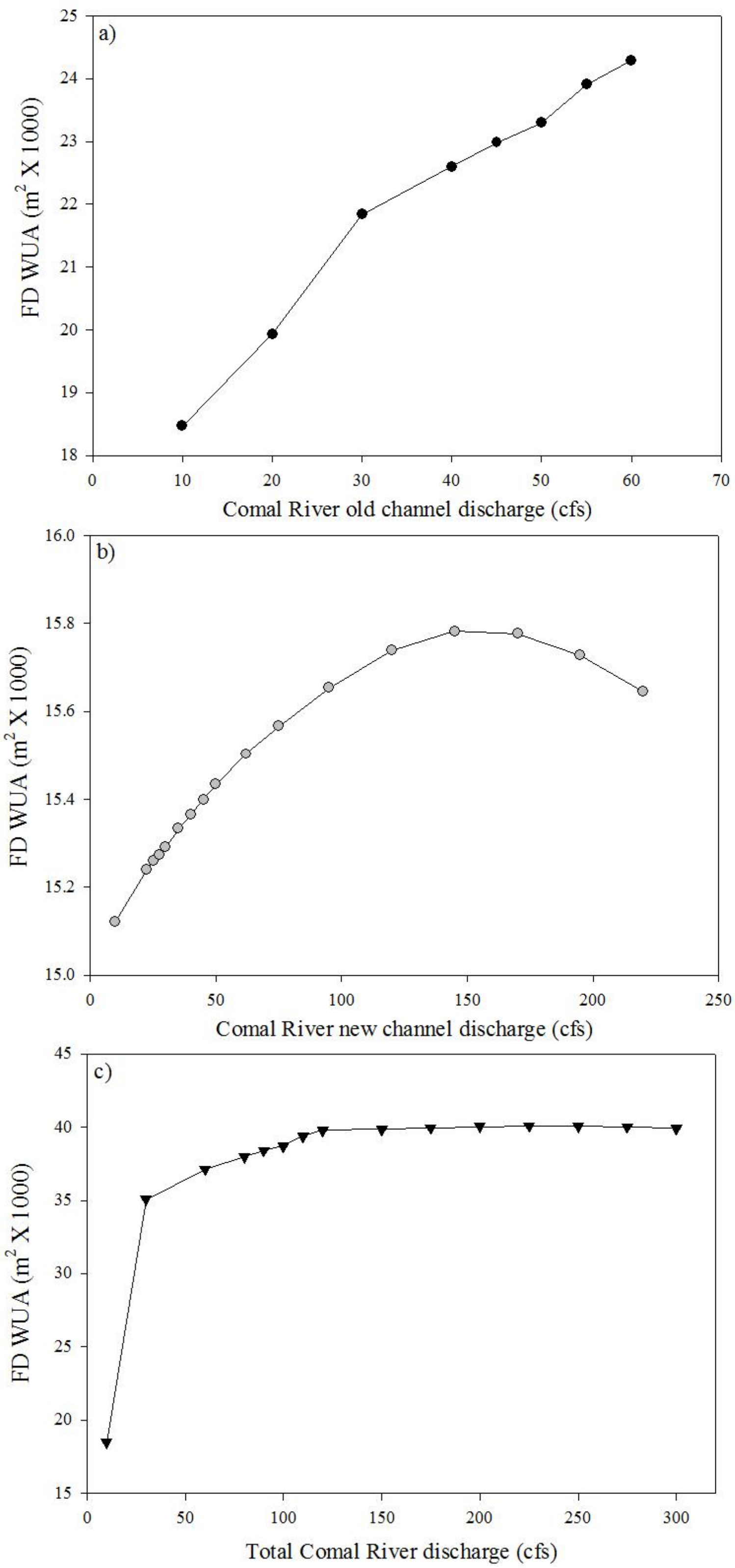


Figure 48. **Weighted usable area (WUA) for fountain darter at various discharges within the Comal River.**

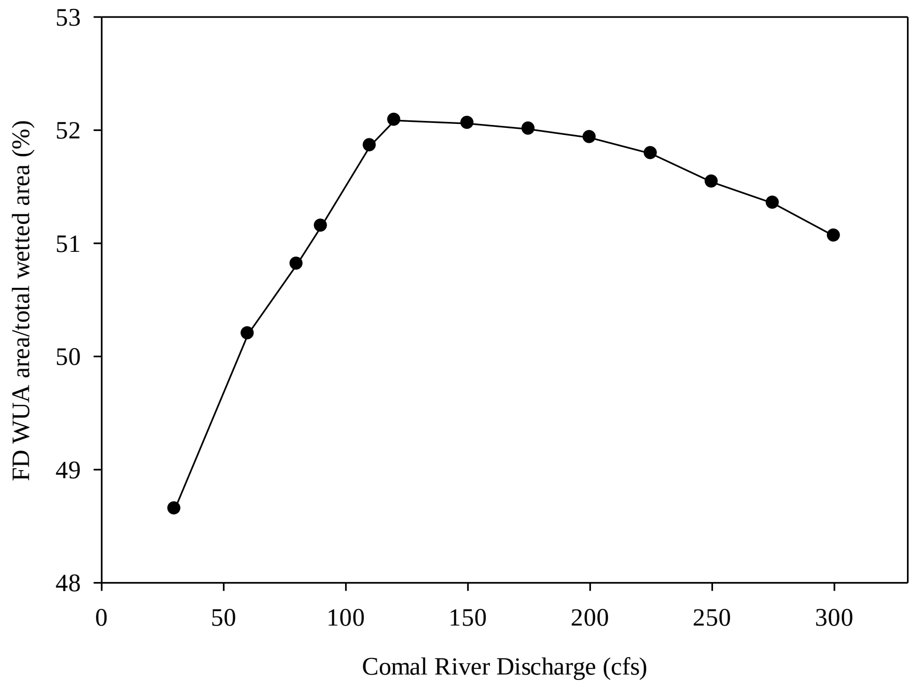


Figure 49. **Percentage of total surface area predicted as weighted usable area (WUA) for fountain darter under various discharges within Comal River.**

It is important to stress that these results assume that the aquatic vegetation mosaic within Landa Lake, the upper new channel, and the old channel will be maintained under these flow regimes. A large change in the availability of aquatic vegetation has the potential to reduce available darter habitat at a given discharge and the effect has been observed based on monitoring of vegetation and darters within the Comal River (BioWest 2010a). This stresses the need to ensure proposed EARIP mitigation measures for control of non-native species that have the potential to impact the aquatic vegetation such as suckermouth catfish, tilapia, rams horn snails, etc can be successfully implemented. Based on the simulation of available physical habitat over the flow regime being considered by the EARIP, the results indicate that sufficient darter habitat will be maintained within the Comal River. Implications of the flow regime from a vegetation dynamics and thermal perspective are discussed below.

Implications of Temperature on Fountain Darters

The calibrated Qual2e model was used to simulate a range of discharge within the Comal River on an hourly basis. As noted in the Methods Section, July 15th was chosen as a representative day given the similarity of results over the entire month of July. Figures 50 through 54 show a comparison between the hourly simulated temperatures for several reaches within the Comal River at 30 and 80 cfs.

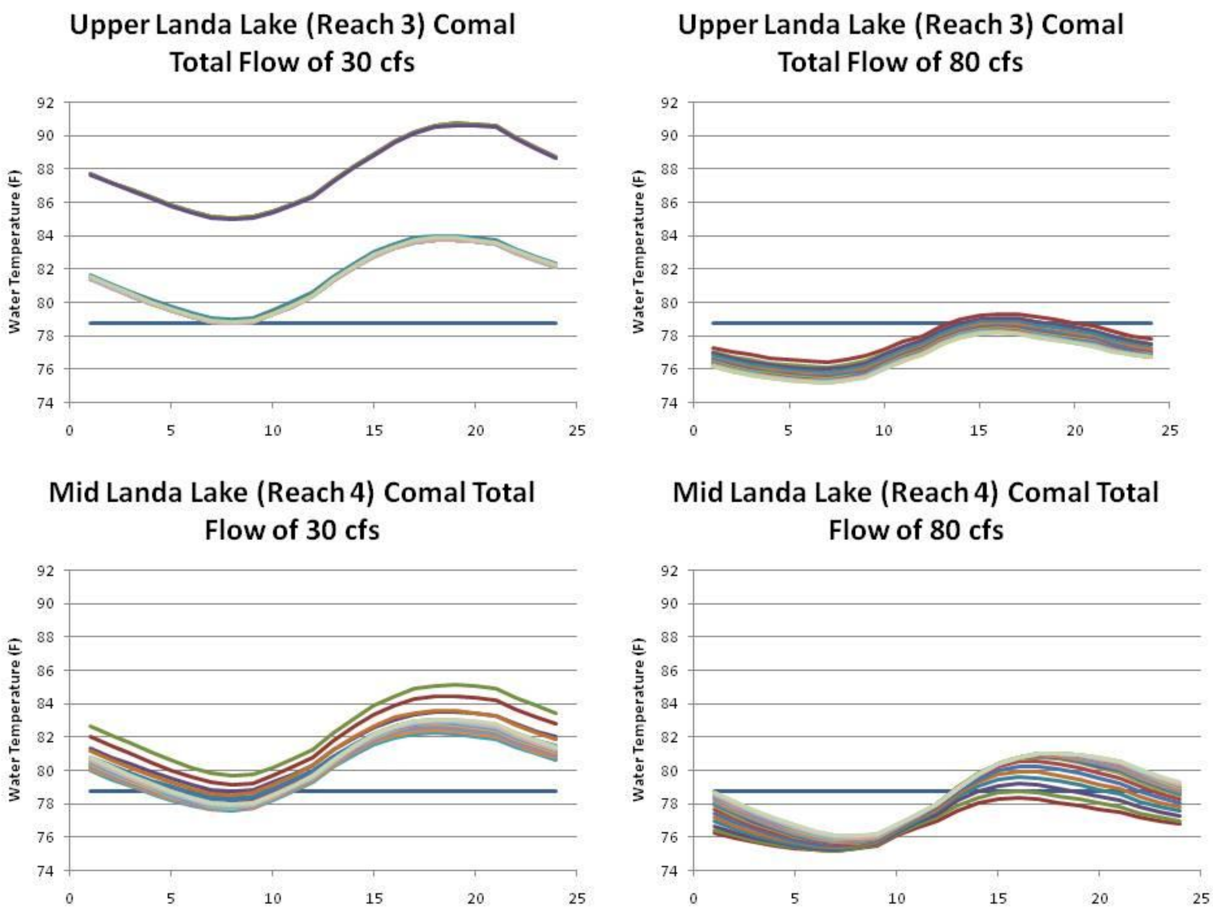


Figure 50. **Simulated hourly temperature profiles in Reach 3 and 4 of the Comal River at 30 and 80 cfs. Flow in the old channel was assumed to be 20 and 60 cfs respectively.**

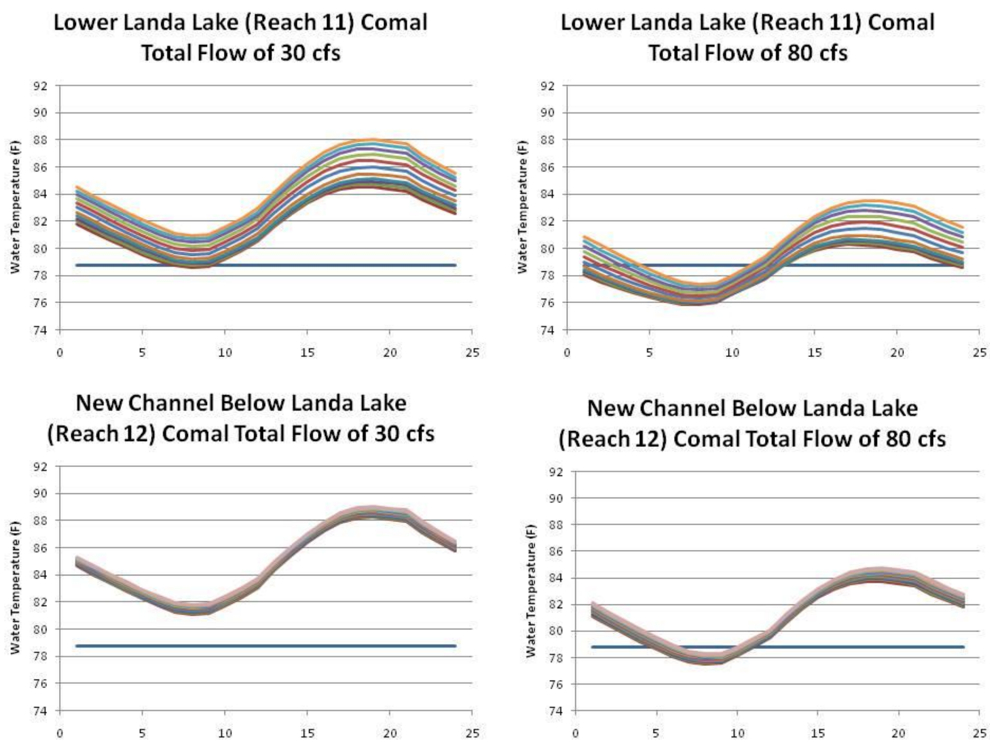


Figure 51. **Simulated hourly temperature profiles in Reach 11 and 12 of the Comal River at 30 and 80 cfs. Flow in the old channel was assumed to be 20 and 60 cfs respectively.**

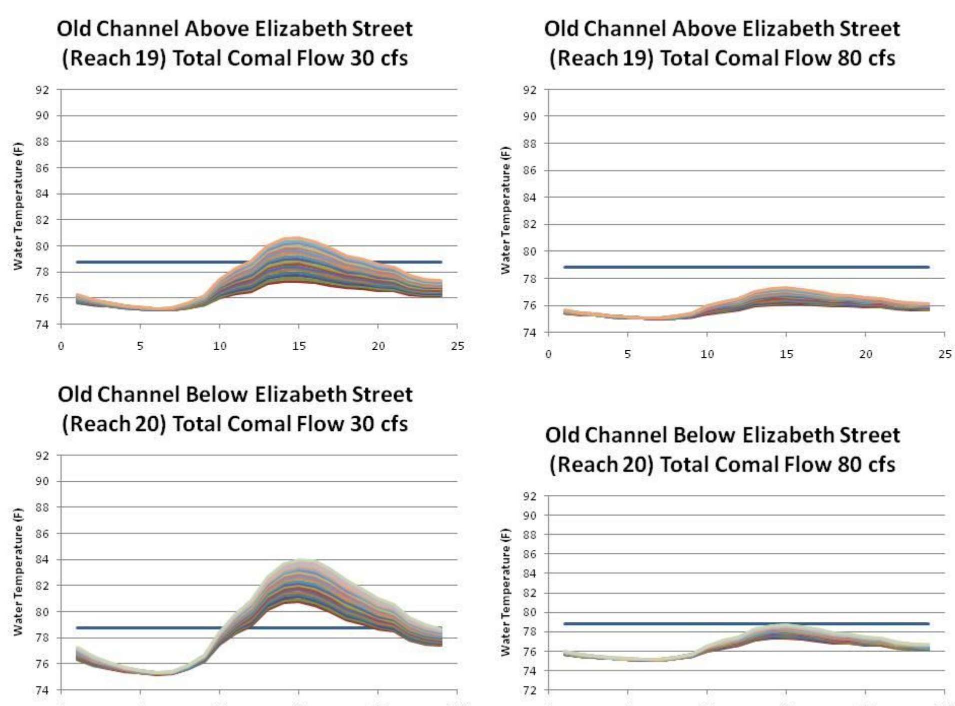


Figure 52. **Simulated hourly temperature profiles in Reach 19 and 20 of the Comal River at 30 and 80 cfs. Flow in the old channel was assumed to be 20 and 60 cfs respectively.**

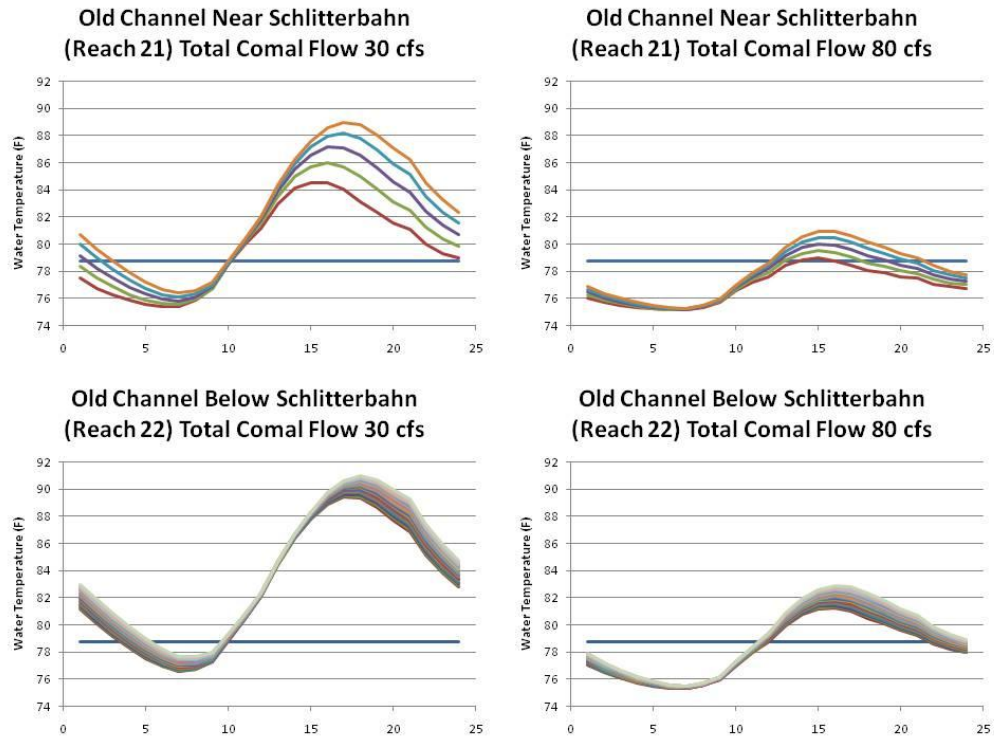


Figure 53. Simulated hourly temperature profiles in Reach 21 and 22 of the Comal River at 30 and 80 cfs. Flow in the old channel was assumed to be 20 and 60 cfs respectively.

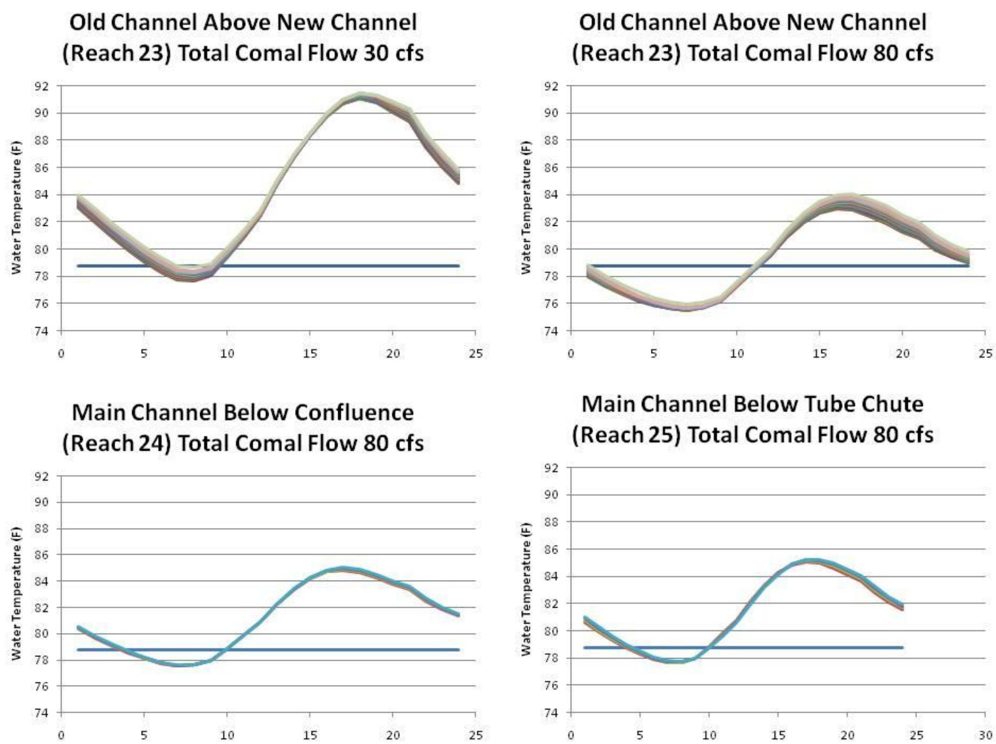


Figure 54. Simulated hourly temperature profiles in Reach 23 and 24 of the Comal River at 30 and 80 cfs. Flow in the old channel was assumed to be 20 and 60 cfs respectively.

The results clearly show that the upper extant of Landa Lake at 30 cfs results in all hourly simulated temperatures that exceed both the darter larval mortality increase and cessation of viable egg production thresholds. However, the influence of spring inflows near the lower boundary of the reach are evident (see Figure 50) and reduce the maximum daily temperatures below the viable egg production threshold for all hourly simulations. Contributing spring flows at 80 cfs show that only a few hours in late afternoon are expected to marginally exceed the larval mortality threshold value.

Increasing contributions from springs within the mid-Landa Lake area at 30 cfs are somewhat offset by thermal loading from the upper lake and maximum daily temperatures basically remain above the larval mortality threshold but below the viable egg production threshold. At 80 cfs, larval mortality thresholds are exceeded in this reach for a few hours each day except at the most downstream 200 feet of the reach (see Figure 50). Lower Landa Lake at 30 cfs exceeds the larval mortality threshold for all hours of the day while at 80 cfs there is a five or six hour period during the early morning hours where water temperatures fall below the larval mortality threshold and always remain below the viable egg production threshold.

At 30 cfs, it is assumed that only 10 cfs remain in the new channel and at 80 cfs only 20 cfs remains in this section of the Comal River. It is not surprising therefore that the results for the new channel above the power plant exceed both the larval mortality threshold and for several hours each day exceed the viable egg production threshold at 30 cfs. At 80 cfs, the larval mortality threshold is almost always exceeded except for all but a few hours but water temperatures always remains below the viable egg production threshold. The remainder of the new channel below the power plant and upstream of the confluence with the old channel at 30 cfs remains above the larval mortality threshold and increasing hours of each day exceeds the viable egg production threshold. At 80 cfs, this section of the new channel remains above the larval mortality threshold but below the viable egg production threshold for all hours of the day.

At a total Comal River discharge of 30 cfs, the old channel maintains water temperatures well below the viable egg production threshold, with water temperature exceeding the larval mortality threshold for less than half a day in all reaches above Schlitterbahn (see Figures 52 through 54). At this flow rate (assumed 20 cfs in the old channel), the old channel reaches at Schlitterbahn and below exceed the larval mortality threshold for most of the day and exceed the viable egg production threshold for several hours each day. In contrast, at a total Comal River discharge of 80 cfs (assumed 60 in the old channel), the old channel water temperatures always remain below the viable egg production threshold and show only a few hours each day that exceed the larval mortality threshold through Reach 22 (below Schlitterbahn). The reach above the confluence with the new channel shows that during the later afternoon, water temperatures exceed the larval mortality threshold for approximately 12 hours (see Figure 53). The relatively hot new channel water tends to overwhelm the somewhat cooler water from the old channel at both the 30 and 80 cfs total Comal River discharge below the confluence and result in most of the day having water temperatures that exceed the larval mortality threshold and approach the viable egg production threshold for a few hours in late afternoon.

Figure 55 provides a spatial overlay of the anticipated darter habitat that incorporates thermal conditions within the Comal River System at 80 and 30 cfs, respectively. Although the plot for 30 cfs does not reflect habitat within Landa Lake at the 30 cfs flow, we believe that the current temperature simulations somewhat over predict the thermal impacts in lower Landa Lake to some extent. Qual2e simulations assume complete vertical mixing within each computational element and therefore is insensitive to density gradients due to differential water temperatures from point loads (i.e., springs). This likely results in an 'over stating' of the thermal impacts in Lower Landa Lake based on these simulations. Direct observations of a fully developed boundary layer have been observed in Landa Lake in association with aquatic vegetation (T. Hardy personal observation). Field measurements of the vertical velocity profiles over thick vegetation beds shows that near bed velocities are very low and can be 'hidden' from mixing of surface layer water that streaming over the top of the vegetation (Hardy et al., 1998). The strong association of darters to specific vegetation types also reflects their preference for these developed boundary layers. These facts motivated Hardy et al. (1998) to incorporate vegetation specific vertical velocity profiles to estimate the hydraulics near the bed in assessing darter habitat. From a thermal perspective, we hypothesize that 'thermal refugia' are likely to develop in association with cooler water (i.e., denser water) discharges from the lake bottom, especially in association with dense aquatic vegetation that are not accounted for in the present assessments of suitable habitat over the lower flow ranges being evaluated. Plots of thermograph data within Landa Lake in near lake bottom spring sources versus nearby open lake areas exposed to current in the Spring Island reach tend to support this hypothesis (BioWest 2010a).

Figure 55. **Spatial extant of suitable darter habitat based on thermal criteria (see text for explanation) At 80 cfs total Comal River flow, the old channel has 60 cfs while at a total Comal River flow of 30 cfs the old channel has 20 cfs.**

Implications of Flow Regime on Vegetation Dynamics

A critical assumption in the foregoing assessments is that the flow regime being evaluated will not have a substantial negative impact on the distribution or density of the aquatic plant community. Vegetation monitoring over the past decade suggests that at flow levels being considered within the old channel (i.e., ~ 20 to 60 cfs) that low flow related impacts to the aquatic vegetation are not likely to be substantial (BioWest 2010a). Scour from higher discharges appear to be more disruptive to the aquatic plant community in the old channel and was the motivation for restricting the maximum flow rate into the old channel at 60cfs in these assessments. The monitoring of the aquatic plant community after the floods in 2010 will provide important data on understanding the vegetation dynamics in the old channel and at a broader level within Landa Lake.

Additional uncertainties are related to the aquatic vegetation response to sustained conditions of low flow regimes within Landa Lake. Although episodic low flow periods have occurred since the drought of record, very little quantitative data exists on the vegetation distribution and density prior to and for longer periods after these events. What is known is that Landa Lake over the past decade of monitoring has maintained a vibrant aquatic plant community.

Figure 56 shows that the lower extant of Landa Lake is primarily dominated by mud sediments which can have a high potential for sediment oxygen demand under the right conditions. Matlock et al. (2003) have shown that areas with high sediment deposition potential typically have high sediment oxygen demand but can range over three orders of magnitudes. It is unknown at this point what the sediment oxygen demand potential is for the sediments within Landa Lake and what impact they may have on dissolved oxygen profiles under sustained low flow events and needs to be addressed early in the proposed adaptive management process of the EARIP.

The response of the aquatic plant community to increased residence times in Landa Lake as a function of total Comal River discharge (Figure 57) is also uncertain. Residence time can be broadly viewed as the inverse of the expected magnitude of the velocity fields within Landa Lake. Specifically, as total spring discharge drops from 80 to 30 cfs, the overall magnitude of the velocities through Landa Lake will be substantially reduced. This in part is a function of the overall topography of the lake and in part due to maintenance of the lake elevation through control structures.

Response of aquatic plants to changes in velocity and other factors is a very complex interrelated dynamic between physical, chemical, and biological processes and varies greatly across vegetation species. For example, reduced water flow can result in increased accumulation of organic matter that can increase the concentration of phytotoxins in the sediment and lead to an increase in oxygen demand by the roots which, if not met due to poor light availability, has the potential to kill the plants (Robblee et al. 1991; Carlson et al. 1994). As flow is reduced, thicker blade diffusion boundary layers will form due to reduced current velocity in aquatic vegetation beds (Koch 1994). The diffusive boundary layer (DBL) is a thin (10's to l00's of *um*) layer of water on the surface of any submersed object (including plants) where the transport of solutes (e.g., carbon needed for photosynthesis or oxygen produced by photosynthesis) is dominated by diffusion processes. As the thickness of this DBL increases with decreasing current velocities it results in a longer diffusional path (thick DBL) for carbon molecules to move from the water column to the plant leaf, where they are used for photosynthesis.

As the current velocity decreases, a critical DBL thickness, where the flux of carbon to the plant does not meet the requirement to support maximum photosynthesis, can be reached (Jones et al. 2000). If a plant is exposed to DBL thicknesses greater than the critical DBL thickness (i.e., reduced current velocity or thick epiphytic layers) for long periods of time, the plant can die due to carbon limitation independent of the light levels (Jones et al. 2000). The length of time that a plant can survive under such conditions depends on the internal carbon reserves in the plant tissue and how fast these reserves can be accessed (Koch 1993). Unfortunately, this has not yet been determined for most submerged aquatic plant species but has the potential to be important in areas where stagnant flow conditions in aquatic plant habitats occur. Given the topography within Landa Lake and based on the existing hydraulic simulations, some areas within Landa Lake may in fact become stagnant at the lower discharges being considered.

A literature review by Koch (2001) shows that the range of current velocities tolerated by marine angiosperms (seagrasses) lies between approximately 5 and 180 cm/s (physiological and mechanical limits, respectively). The range of current velocities tolerated by freshwater angiosperms seems to be generally lower than that for the marine species; and some freshwater species can tolerate extremely low current velocities due to alternative mechanisms of carbon acquisition (polar leaves). This review suggests that intermediate current velocities (possibly between 5 and 100 cm/s) are needed to support the growth and distribution of healthy seagrass beds. These requirements are lower for freshwater/estuarine species (possibly between 0 and 50 cm/s), especially for those with polar leaves. If currents are above or below these critical levels, the feedback mechanisms in the system may become imbalanced and possibly lead to the decline or even complete loss of the vegetation.

Vegetation dynamics in shallow lakes are also influenced by complex interactions with dissolved inorganic carbon (DIC), periphyton, macroinvertebrates, and fish. DIC concentration has the potential to influence community structure in shallow lakes, altering competitive interactions between periphyton and plants and rendering low DIC lakes more prone to loss of plants when nutrient loading increases. However, the expression of this competition between periphyton and plants will depend on the density of grazing invertebrates present, which is itself influenced by the intensity of fish predation on those invertebrates (Jones et al., 2002). Jones and Sayer (2003) found that the density of periphyton on aquatic plants was correlated with the density of grazing invertebrates, not nutrient concentration. In turn, the biomass of fish determined the density of invertebrates. This cascade from fish to periphyton via invertebrates appeared to be evident even though plant-dominated lakes are heterogeneous and complex. Under conditions of plant dominance, periphyton appeared to have a stronger influence on plant growth than phytoplankton. The range of nutrients where alternative equilibria are possible, fish are the prime determinants of community structure in shallow lakes, through a cascading effect of predation on grazing invertebrates influencing the biomass of periphyton and hence, plants.

What these studies reveal is that control of non-native species that can directly or indirectly impact the aquatic vegetation needs to be effective under proposed EARIP mitigation measures. Furthermore, directed research on the implications of the flow regimes, specifically the residence time and velocity fields, on aquatic plant dynamics needs to be undertaken early in the adaptive management process to better inform the adequacy of the flow regimes being contemplated by the EARIP.

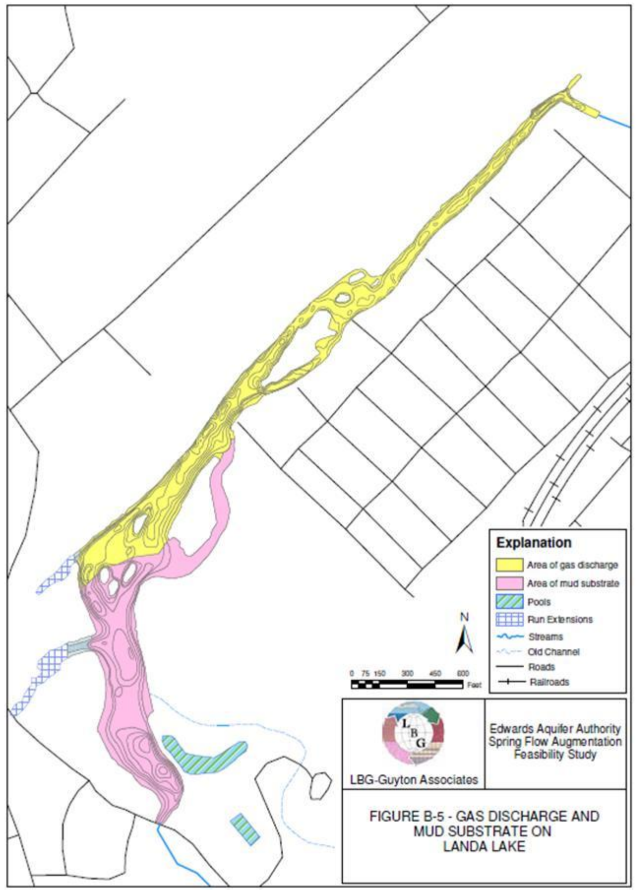


Figure 56. **Distribution of sediment types within Landa Lake (Guyton Associates 2004).**

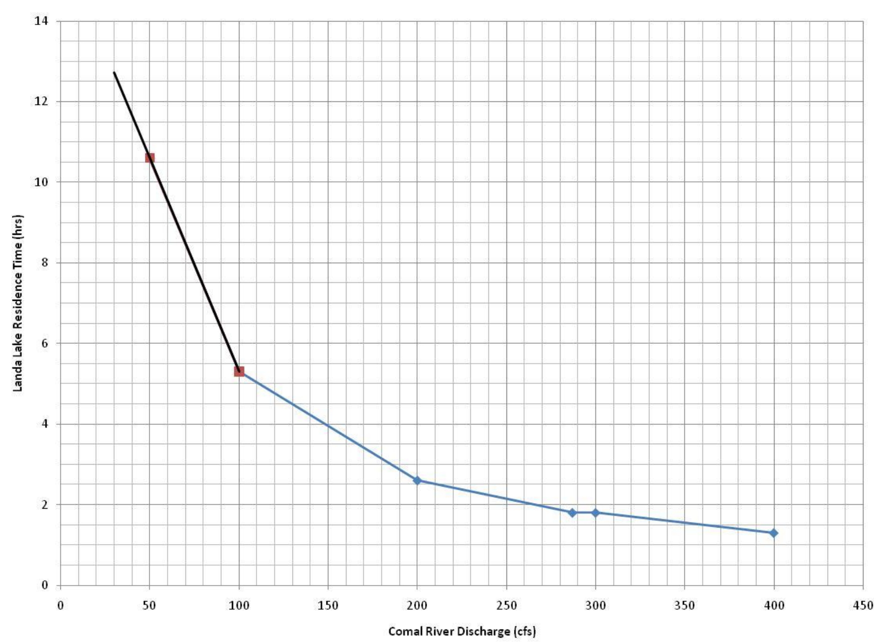


Figure 57. **Relationship between Landa Lake residence time and total Comal River discharge.**

Comal Springs riffle beetle

Water surface elevations as a function of discharge were used to assess lake elevations at discharges between 30 and 80 cfs specifically along the western margin of Landa Lake and in the region of Spring Run 3 and lower extant of Spring Runs 1 and 2. These results show that at 30 cfs, the western spring orifices will remain below Landa Lake water surface elevations. The lake topography and water surface elevation at a total Comal River discharge of about 60 cfs, indicates that the lower extant of Spring Run 3 becomes inundated and approximately 1/3 of the lower spring run is inundated at a discharge of 80 cfs. This is also seen for the combined outflow region for Spring Runs 1 and 2 although the aerial extent of inundation is somewhat less at this location at both 60 and 80 cfs. This strongly suggests that additional subsurface spring flows are likely over this discharge range in these areas. This is likely to provide positive benefits to the Comal Springs riffle beetle. Incremental increases in flow at these locations would contribute to reductions in the lake water temperatures that would be beneficial to darters.

We believe the empirical data on riffle beetles demonstrates their persistence within the Landa Lake and spring runs over the past two decades strongly supports that they should be adequately protected over the proposed flow regime being considered by the EARIP. Springs along the western margin of Landa Lake are anticipated to provide adequate habitat during the lower flow regime and in our opinion as flow increases to the 80 cfs range that the lower extant of Spring Runs 1, 2 and 3 will be hydraulically connected to Landa Lake given expected lake elevations and lake bathymetry. In this context, hydraulically connected refers to increased phreatic flows to Landa Lake below the water surface elevation of Landa Lake and increased aerial inundation along the lower spring run areas.

We understand that previous extirpations may have resulted in some shifts in genetic makeup between the various populations spatially within Landa Lake and that population densities prior to their extirpation in the 1950's is unknown. It is clear however, that maintaining spring flows within Landa Lake along the western margin in occupied beetle habitats will persist. Our review of the water quality data do not indicate any demonstrable shift in water temperature or quality that would suggest that at these lower flow rates, impacts from water quality would be expected.

Summary

The modeling and analysis of data presented in this report generally supports the proposed target flow regimes being contemplated by the EARIP specific to the drought of record. As noted at the beginning of this report, these flow regimes are not sustainable on a long term basis and are specific to maintaining adequate habitat conditions and populations of target aquatic resources within the Comal and San Marcos River systems to permit long-term sustainability of the populations after a repeat of the drought or record. In total, it is our opinion that the flow regimes in the Comal and San Marcos Rivers will provide adequate protection for the aquatic resources given the underlying assumptions and the mitigation measures proposed by the EARIP have been successfully implemented.

We believe the greatest uncertainties underlying our assessments within the Comal River are related to vegetation dynamics in Landa Lake, characteristics of the hydrodynamic velocity fields that are assumed to allow the cooler spring water issuing from the lake bottom to actually make it to the old channel culvert system, and successful parasite and non-native (fish) control. It is unknown at this time if the proposed flow regime within the Comal River will result in substantial vegetation die-off with resulting deleterious diel oxygen depressions to levels lethal to darters or other aquatic resources. Although the existing pilot project on parasite control using snail removal is promising, full scale efforts should be demonstrated over a several year period. We also believe that an aggressive non-native fish control program needs to be initiated and shown to be effective over time. We believe that darter populations will persist at reasonable numbers both within Landa Lake and upper reaches of the old channel with the flow regime magnitudes currently being considered. The old channel in particular will sustain both reproduction and recruitment at flow rates between 20 and 60 cfs based on physical habitat and temperature modeling results and are further supported by the available biological monitoring data from the old channel collected over the past decade.

The analysis of habitat and temperature within the San Marcos River strongly suggest that adequate protection will be provided for the aquatic resources given the proposed flow regime being contemplated by the EARIP. One area of uncertainty for the San Marcos is related to successful recreation control for target TWR stands and successful implementation of mitigation surrounding removal of non-native vegetation that subsequently is occupied by TWR. However, we believe that our analysis of non-native vegetation removal is conservative and supports our conclusion that TWR populations can likely be increased in protected areas to further ‘buffer’ this species against potential negative impacts over the lower flow regime discharges. We further reiterate the importance that these opinions assume all other mitigation measures are successfully implemented and would include non-native (fish) control, etc.

Recommendations

Much of the uncertainty surrounding the evaluations of the proposed flow regimes in the Comal and San Marcos River are related to assumptions on the biological responses of target aquatic species and in part to estimated conditions within the rivers at lower flow rates. Another critical element is related to the assumptions that all the various mitigation measures can be successfully implemented. The following set of recommendations is provided based on the experience gained from the modeling exercises and assessments in this report and overall experience working in these two river systems. They are provided in the hope that it will help guide some of the priorities of the envisioned Adaptive Environmental Monitoring Program being contemplated by the EARIP.

1. It is strongly recommended that a pilot study be initiated for evaluating TWR planting and non-native vegetation removal in areas predicted to have optimal depth and velocity conditions. Replicated test areas based on the simulations of mixed stands of TWR in optimal occupied areas, TWR simulated optimal areas but not occupied, and TWR simulated areas of optimal habitat containing non-native species should be identified for field trials. In mixed stand areas, the non-natives should be removed and the stand monitored. Optimal but unoccupied areas should have vegetation removed and TWR plants planted and monitored. For occupied optimal areas of TWR with adjacent non-native vegetation, the non-native plants should be removed and the stand monitored. The specific areas chosen for field trials should consider only areas that would be suitable over the full range of discharges between the long term average and the lower anticipated EARIP minimum flows.

2. Updated topography from Pecan Island area downstream to the Landa Lake weir should be collected to reflect existing topography after the 2010 flood. A review and selection of a 3-dimensional hydrodynamic temperature model should be undertaken with a goal to critically evaluate the 3-dimensional flow fields in this section of the lake. Dye injection (or other method) at the at the spring locations along the western margin of Landa Lake upstream from Spring Run 3 should be used to quantitatively evaluate the flow fields in this section of the lake. These data should be used to validate the 3-dimensional hydrodynamic model to confirm that at the lower flow rates in the range of 80 to 30 cfs will propagate the cooler water to the vicinity of the culverts to the old channel and not follow flow paths down the new channel. It should also be utilized to quantitatively assess the potential magnitude and location of expected thermal refugia associated with spring inflows.

3. The updated hydrodynamic model should also be used to better quantify the expected velocity magnitudes within lower Landa Lake to help design flume and/or microcosm experiments with existing aquatic vegetation using aquifer source water to examine plant health and growth dynamics under assumed flow rate ranges between 30 and 80 cfs. This is critical to determine the realistic expectation of vegetation dynamics in lower Landa Lake under these regimes.

4. Sediment oxygen demand potential for lower Landa Lake should be critically evaluated.

5. Recreation control measures should be implemented and tested in sections of the San Marcos River during peak recreation periods to evaluate the effectiveness and feasibility of protecting target TWR stands.

6. Laboratory experiments using colloidal material to mimic the downstream 'bio-turbidity' due to recreation on TWR plant growth and health should be undertaken. This may represent an existing limiting factor not presently well understood that could hamper restoration efforts in the lower sections of the San Marcos River.

7. Selective non-native fish removal efforts should be initiated in both the San Marcos and Comal River systems to demonstrate that effective control measures can be implemented.

8. Based on the pilot study for snail removal and parasite concentration responses, full scale snail control and parasite monitoring should be initiated in the Comal River to demonstrate how effective the mitigation measure will actually be over an extended period.

9. Other mitigation measures being considered by the EARIP that have a 'field component' should have appropriate field level trials or laboratory studies initiated as early in the process as feasible.

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