Effects of changing height of Cape's Dam on recreation, Texas wild rice and fountain darter habitat in the San Marcos River, Texas

Prepared for:

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October 12, 2015

EXECUTIVE SUMMARY

Modeling of aquatic habitats and water based recreation in the San Marcos River associated with Cape's Dam simulated at full height, half height or complete removal was completed using advanced hydraulic modeling which allowed the river bed to adjust due to sediment transport under these three assumed conditions. The results demonstrate that with full dam removal, the San Marcos River in the vicinity of Cape's Dam will revert to normal flow depths similar to existing free flowing sections below Rio Vista and downstream of Thompsons Island. Deep pool areas (e.g., just downstream of the IH35 access road, the plunge pools below the location of Cape's Dam and the outfall pool below the Mill Race will remain over 3-6 feet deep <u>even</u> when river flows are 45 cfs which is a flow rate that was observed for one day during the drought of record. These areas will retain even greater depths at 100 cfs which is a daily flow rate that is equaled or exceeded 90 percent of the time.

Full height or half height Cape's Dam scenarios provide no demonstrable environmental benefits to the native aquatic or riparian species within the San Marcos River. Rebuilding Cape's Dam will continue to impact native aquatic species due to habitat fragmentation, reduction in habitat quality and continue to maintain a passage barrier. These negative impacts are associated with loss of native species diversity. Diversion of water into the Mill Race under half height or full height dam conditions will continue to result in reduced flows within the main channel of the San Marcos River and contribute to reductions in habitat conditions for the native aquatic species especially under low flow conditions.

Results clearly demonstrate that habitat conditions for aquatic macrophytes including the endangered Texas wild rice show the greatest benefits with full dam removal at all simulated flow rates. Full dam removal is expected to result in increased aquatic macrophyte growth due to better light penetration to the stream bottom with removal of the backwater conditions upstream from Cape's Dam. Dam removal will also result in an increase in the distribution of higher velocities within this section of river that are beneficial to Texas wild rice. Texas wild rice shows diminished growth and survival in low and no velocity areas reflective of backwater conditions upstream of Cape's Dam.

Dam removal results in improved fountain darter habitat over all simulated flows. The improvements in fountain darter habitat conditions under removal of Cape's Dam are underestimated since they do not reflect the habitat gains that will occur due to increased stream coverage from aquatic macrophytes in this section of the river.

Dam removal and subsequent changes in river characteristics (i.e., depth and velocities) will result in a sustainable safe recreation corridor over all simulated flow rates. River characteristics in the Cape's Dam reach without Cape's Dam will be similar to existing free flowing river sections not impacted by backwater effects (e.g., Sewell Park, City Park and downstream of Rio Vista above IH35). Hourly recreation counts conducted daily over the past three years show that these free flowing sections support swimming, tubing, canoeing, kayaking, and paddle boards.

Rebuilding Cape's Dam at full height or half height will require substantial restoration work on the Mill Race given its current deteriorated state with multiple areas of structural failure.

INTRODUCTION

The City of San Marcos is evaluating the implications in terms of the impacts/benefits to recreation and the habitats for the endangered Texas wild rice (TWR) and fountain darters in the San Marcos River if Cape's Dam is rebuilt to full height, modified to half of full dam height, or is removed. The assessment presented here relied upon existing data on river topography, empirical hydraulic and river sediment properties in conjunction with supplemental field data, and habitat models developed at Texas State University (Hardy et al., 2012). Advanced hydrodynamic modeling was utilized to evaluate expected changes in river bed topography due to sediment transport and river bed evolution under full height, half height, and full dam removal that was not considered in the previous modeling evaluations (Hardy et al., 2012). In this report, "full height" refers to Cape's Dam based on topography measured after dam repairs by the USFWS. The resulting evolved river bed topography and associated hydraulic properties were utilized to model TWR and fountain darter habitat, as well as for modeling water depths available for water-based recreation under all three Cape's Dam scenarios. Habitat modeling for TWR and fountain darters followed the general procedures developed by Hardy et al. (2012) that were used in the development of the Edwards Aquifer Habitat Conservation Plan.

METHODS

Study Area

Figure 1 shows the spatial extent of the assessment conducted in the San Marcos River. The study area begins downstream from Rio Vista Dam and extends downstream to the TPWD State Hatchery outflow. This reach of the river encompasses the spatial extent most likely to be affected by the proposed Cape's Dam scenarios and is occupied habitat for the endangered TWR and fountain darters. Empirical data show that the effects of Cape's Dam does not extend far enough upstream to reach Rio Vista Dam, therefore the section of the river between Rio Vista Dam and the upstream extent of the model is not included in this study.

Figure 1. San Marcos River study area.

Figure 2 documents the distribution of the endangered Texas wild rice both above and below Cape's Dam based on historical survey data. This stretch of river (and downstream) also contains the endangered fountain darter. The Edwards Aquifer Habitat Conservation Plan has identified specific long term biological goals for Texas wild rice in this section of river as illustrated in Table 1.

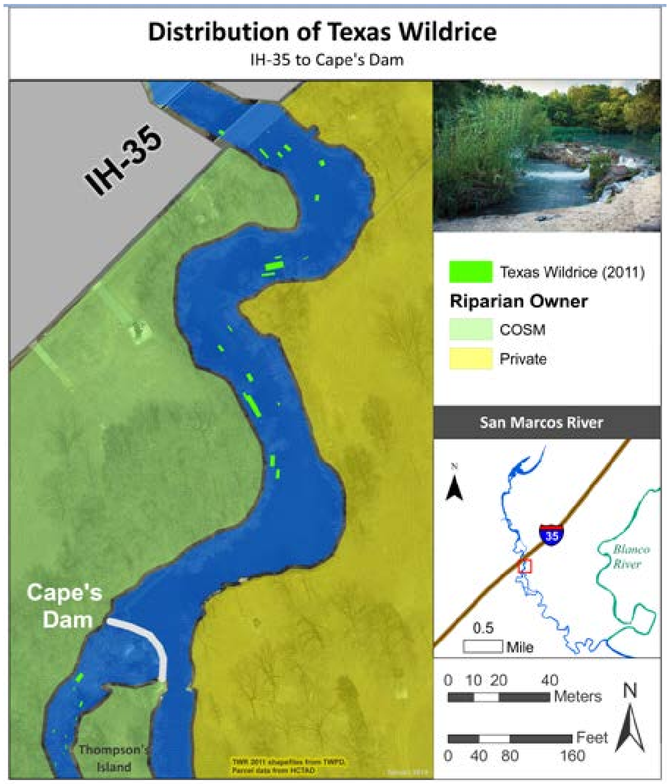


Figure 2. Spatial location of Texas wild rice above and below Cape's Dam in the San Marcos River.

Table 1. Edwards Aquifer Habitat Conservation Plan long term biological goals within the San Marcos River.

LONG-TERM BIOLOGICAL GOAL FOR TEXAS WILD-RICE

River Segment	Areal Coverage (m^2)	Reach Percentage of Total Areal Coverage
Spring Lake	1,000 – 1,500	n/a
Spring Lake Dam to Rio Vista Dam	5,810 – 9,245	83 – 66
Rio Vista Dam to IH-35	910 – 1,650	13 – 12
Downstream of IH-35	280 – 3,055	4 – 22
TOTAL	8000 – 15,450	100

River Channel Topography, Hydraulic and Substrate/Vegetation Data

Topography (i.e., elevation), substrate, vegetation, and surface water elevation data were 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 channel topography. Data density was approximately 3000 data points per 100 meters of stream length. Latitude (x), longitude (y), depth, and substrate type were recorded at each point. Vegetation within the stream was delineated with polygons and the corresponding percentages of each vegetation or substrate type were recorded for each polygon. Vegetation polygons were spatially joined with the hydrodynamic modeling grids to assign roughness values and vegetation class attributes for habitat modeling of fountain darters and Texas wild rice. Discharge and water surface elevation (WSE) longitudinal profiles were recorded each day during field measurements of channel topography. In addition, substrate data collected by Dr. Paul Hudson from the University of Texas as part of the original modeling efforts in 2012 were utilized and consisted of penetrometer and substrate grab samples at 100 locations upstream of Cape's Dam to estimate particle size distribution and depth of sediments. Lateral scour and bed evolution data were also obtained at fixed cross section locations associated with points where channel changes were monitored after channel dredging occurred in reaches below Cape's Dam (Hudson, 2012). Initial water surface elevations were obtained from the calibrated two-dimensional hydrodynamic models developed at Texas State University (Hardy et al., 2010).

Computational Mesh from River Topography

The process of using river bed topography to generate the computational mesh for use in the hydraulic modeling was accomplished using triangular irregular networks as illustrated graphically in Figure 3.

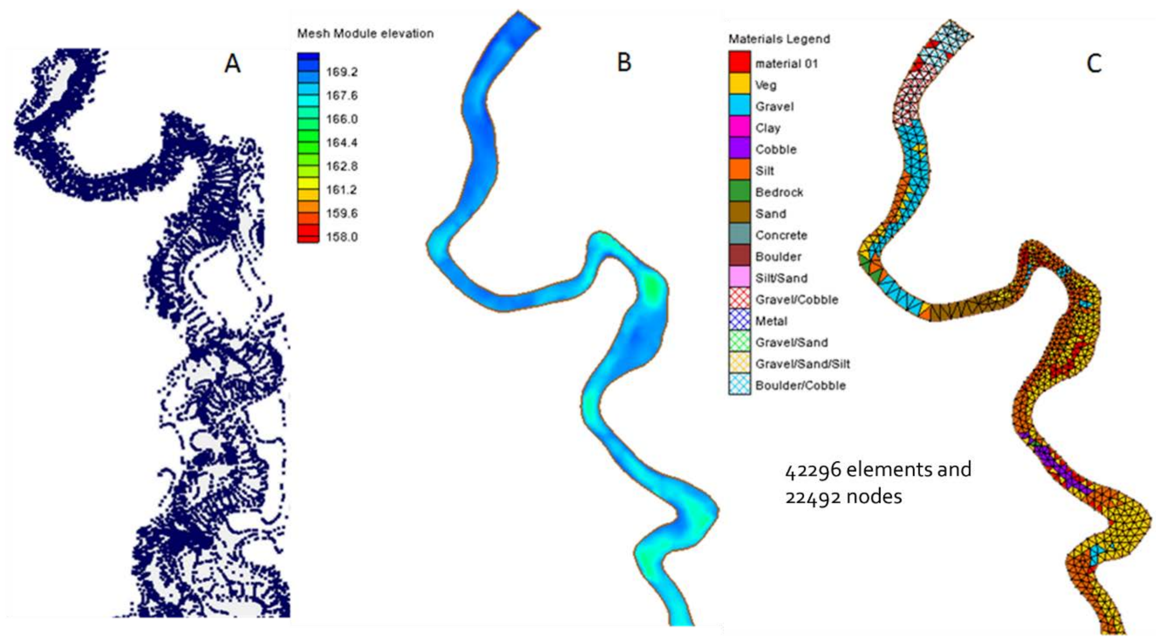


Figure 3. Example of field measured topography points (A) and computational mesh mapped onto elevation contours (B) and substrate (C).

Assumed Cape's Dam Configurations for Full Height, Half Height and Complete Removal

The elevation of Cape's Dam associated with full height conditions was derived from actual historical survey data (Figure 4). These data were used to construct the full height computational mesh to reflect this topography, as shown in Figure 5. The full height computational mesh shown in Figure 5 was lowered by 50 percent and then 100 percent to approximate the starting conditions for the hydrodynamic modeling under the different dam removal scenarios and is illustrated in Figures 6 and 7.

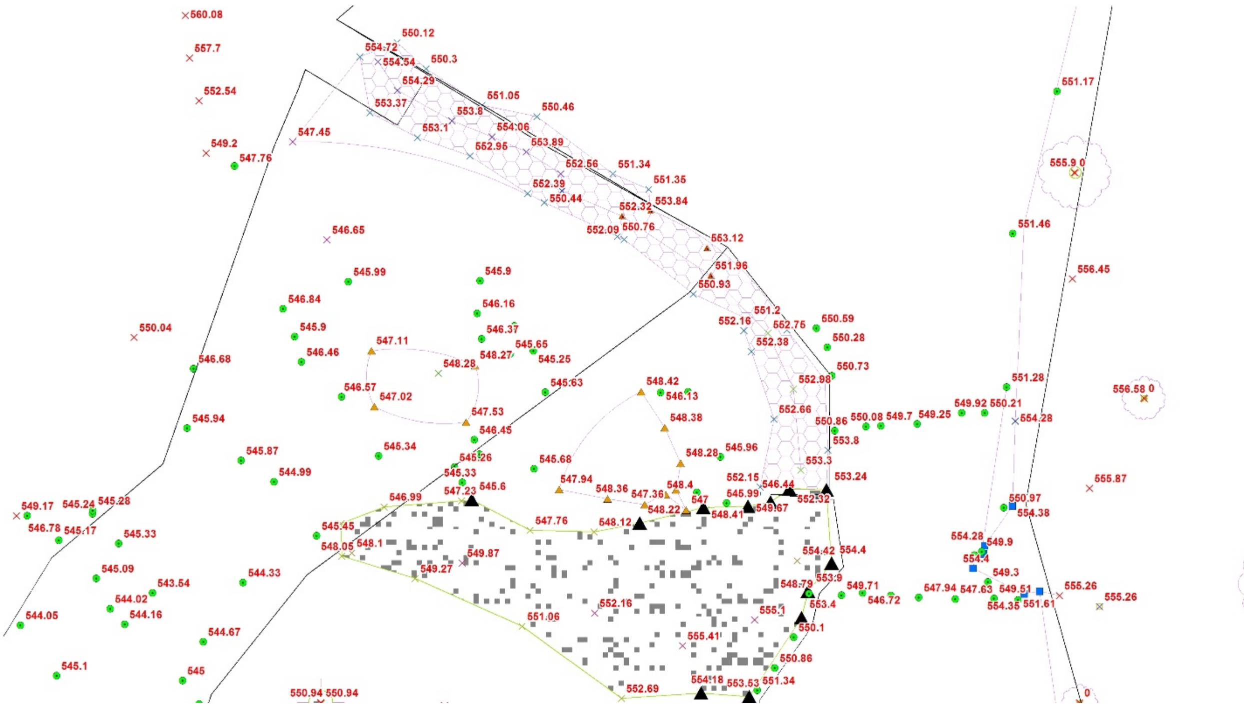


Figure 4. Survey data for full height Cape's Dam.

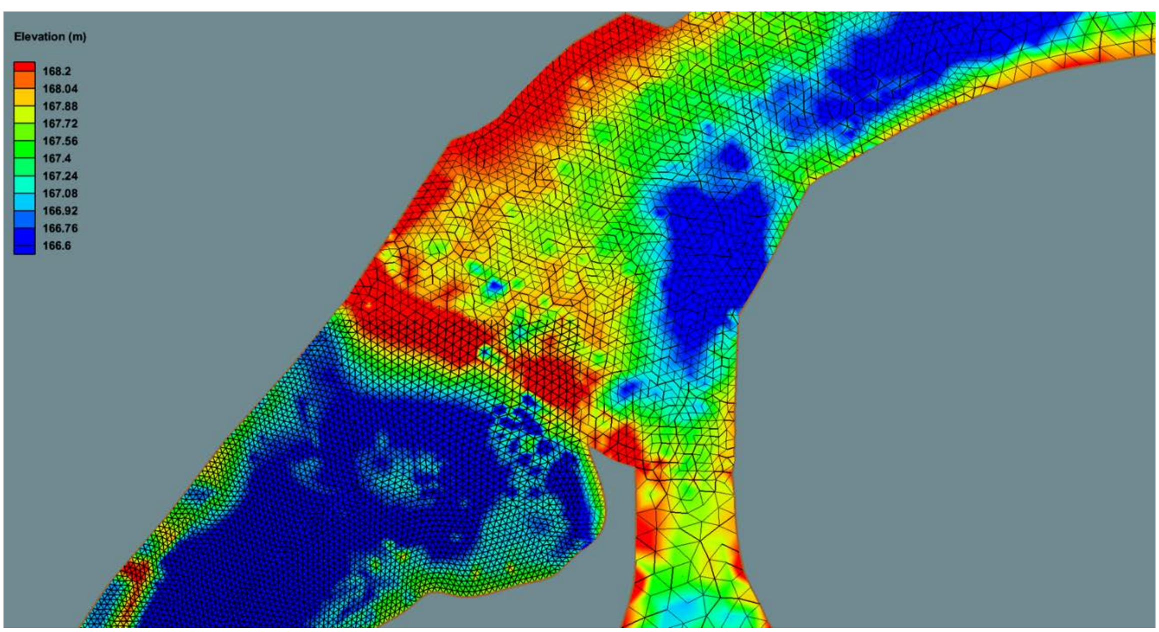


Figure 5. Assumed computation mesh for full height Cape's Dam used in the hydrodynamic modeling.

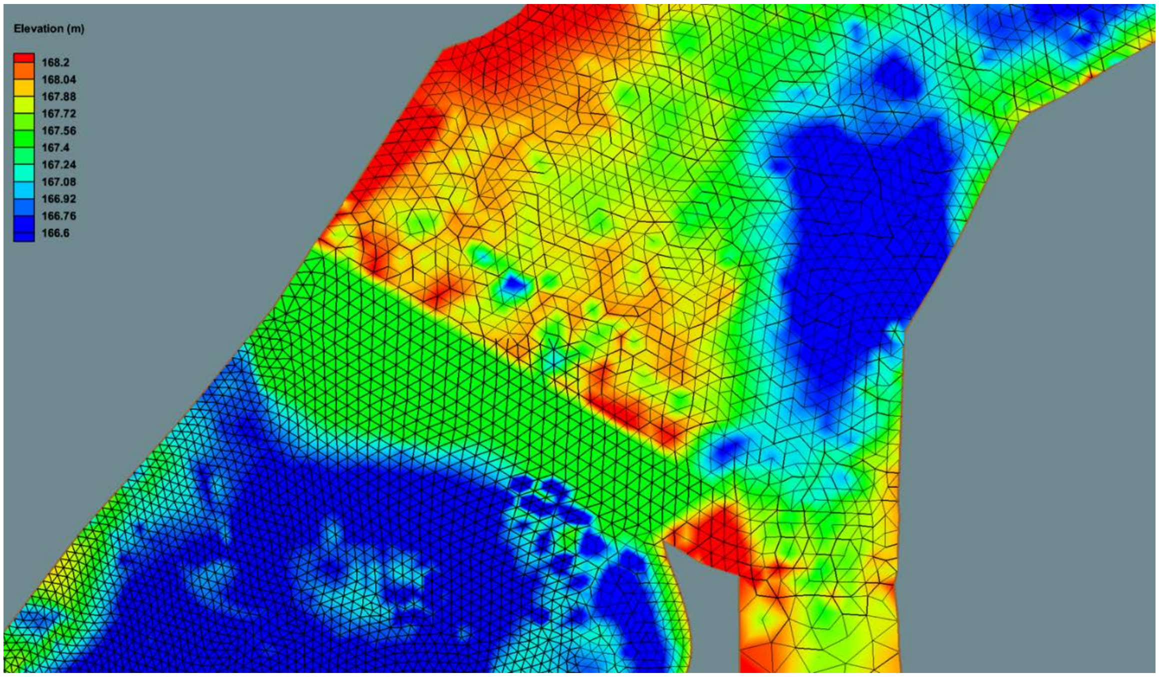


Figure 6. Assumed computation mesh for half height Cape's Dam used in the hydrodynamic modeling.

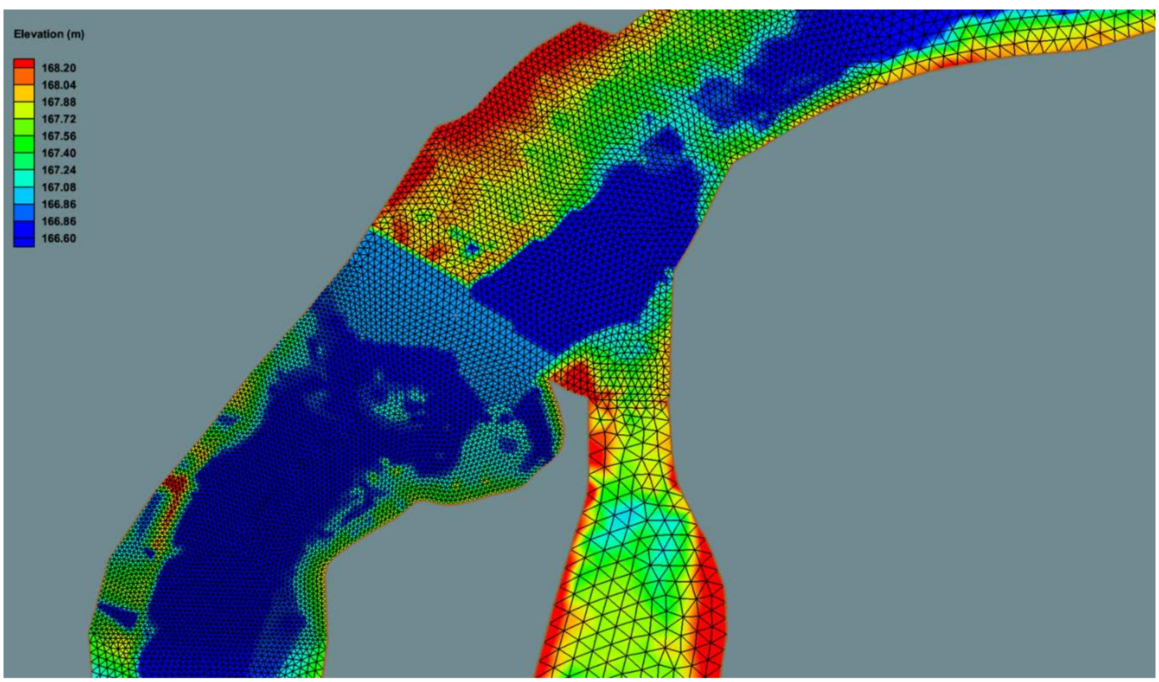


Figure 7. Assumed computation mesh for complete removal of Cape's Dam used in the hydrodynamic modeling.

Note that the half height and full removal topographies are approximations to evaluate channel characteristics after expected sediment transport and river bed evolution and are not meant to represent as-built construction drawings for full height or half height dam scenarios, or the pre-dam natural channel topography under the full removal scenario.

Sediment Characteristics

Channel-bottom sediment polygons over the study area were mapped using GPS and spatially joined with the computational mesh using GIS, as noted previously. However, to support the bed evolution modeling under full height, half height, and complete removal, data from Hudson (2012) was used to characterize the particle size distribution behind Cape's Dam (Table 2) and then spatially interpolate sediment characteristics and sediment depth profiles as illustrated in Figures 8 and 9. Based on these data, Hudson (2012) estimated that ~ 6,700+ cubic meters of fine sediment are trapped behind Cape's Dam. Furthermore as shown in Figures 8 and 9 upward of 3 m (10 feet) of accumulated fine sediments are trapped behind Cape's Dam under existing conditions.

Table 2. Sediment particle size distributions behind Cape's Dam (adapted from Hudson, 2012).

Reservoir bottom sediment samples of Capes Dam							
G=grab sample at bed with sediment sampler; Sh=shallow core sample (0-10 cm); Dp=deep core sample (20-30 cm)							
			Sediment size (mm)				
			D10	D50	D90	Sample type	Location
Sample ID #	X	Y	(10 % finer by weight)	(50% finer by weight, median size)	(90% finer by weight)		
SM-1	-	-	**-**	**-**	**-**	N/A	Thalweg
SM-2-G	N29º 52' 27.9	W097º 55' 52.2	**<0.001**	**0.7**	**>1**	Grab	Inside bend
SM-3-Sh	N29º 52' 27.3	W097º 55' 51.4	**<0.001**	**0.0035**	**0.4**	Core (Shallow)	Outside bend
SM-3-Dp			**<0.001**	**0.005**	**>1**	Core (Deep)	
SM-4-Sh	N29º 52' 27.3	W097º 55' 52.1	**<0.001**	**0.15**	**>1**	Core (Shallow)	Inside bend
SM-5-G	N29º 52' 27.1	W097º 55' 52.3	**<0.001**	**0.26**	**0.7**	Grab	Riffle
SM-6-G	N29º 52' 26.7	W097º 55' 52.8	**<0.001**	**0.16**	**0.5**	Grab	Pool
SM-7-Sh	N29º 52' 27.2	W097º 55' 53.5	**<0.001**	**0.0140**	**0.19**	Core (Shallow)	Outside bend
SM-7-Dp			**<0.001**	**0.0085**	**0.14**	Core (Deep)	
SM-8-Sh	N29º 52' 26.0	W097º 55' 53.4	**<0.001**	**0.0140**	**0.13**	Core (Shallow)	Outside bend
SM-8-Dp			**<0.001**	**0.0013**	**0.13**	Core (Deep)	
SM-9-Sh	N29º 52' 25.8	W097º 55' 52.6	**<0.001**	**0.0020**	**0.20**	Core (Shallow)	Inside bend
SM-9-Dp			**<0.001**	**0.0022**	**0.30**	Core (Deep)	
SM-10-G	N29º 52' 25.2	W097º 55' 53.1	**-**	**-**	**-**	Grab	Thalweg
SM-11-Sh	N29º 52' 24.9	W097º 55' 52.3	**<0.001**	**0.0042**	**0.18**	Core (Shallow)	Left bank
SM-11-Dp			**<0.001**	**0.0090**	**0.26**	Core (Deep)	
SM-12-G	N29º 52' 24.6	W097º 55' 52.5	**<0.001**	**0.31**	**>1**	Grab	Riffle
SM-13-Sh	N29º 52' 24.1	W097º 55' 52.7	**<0.001**	**0.0350**	**0.51**	Core (Shallow)	Inside bend
SM-13-Dp			**<0.001**	**0.0169**	**0.30**	Core (Deep)	
SM-14-Sh	N29º 52' 23.0	W097º 55' 53.5	**<0.001***	**>1**	**>1**	Core (Shallow)	Right bank
SM-14-Dp			**<0.001**	**0.2200**	**0.45**	Core (Deep)	
SM-15-Sh	N29º 52' 23.2	W097º 55' 53.3	**<0.002**	**0.0040**	**0.80**	Core (Shallow)	Left bank
SM-15-Dp			**<0.003**	**0.0035**	**1.00**	Core (Deep)	
SM-16-Sh	N29º 52' 23.3	W097º 55' 52.0	**<0.001**	**0.0025**	**0.11**	Core (Shallow)	Outside bend
SM-16-Dp			**<0.001**	**0.0029**	**0.13**	Core (Deep)	
SM-17-G	N29º 52' 23.1	W097º 55' 53.8	**<0.001**	**0.1300**	**0.45**	Grab	Thalweg
SM-18-G	N29º 52' 27.0	W097º 55' 53.0	**<0.001**	**0.2700**	**0.90**	Grab	Thalweg
SM-19-G	N29º 52' 28.0	W097º 55' 51.7	**<0.001**	**0.1700**	**0.99**	Grab	Thalweg
SM-20-Sh	N29º 52' 28.5	W097º 55' 52.1	**<0.001**	**0.0600**	**0.40**	Core (Shallow)	Left bank
SM-20-Dp			**<0.001**	**0.0300**	**0.33**	Core (Deep)	

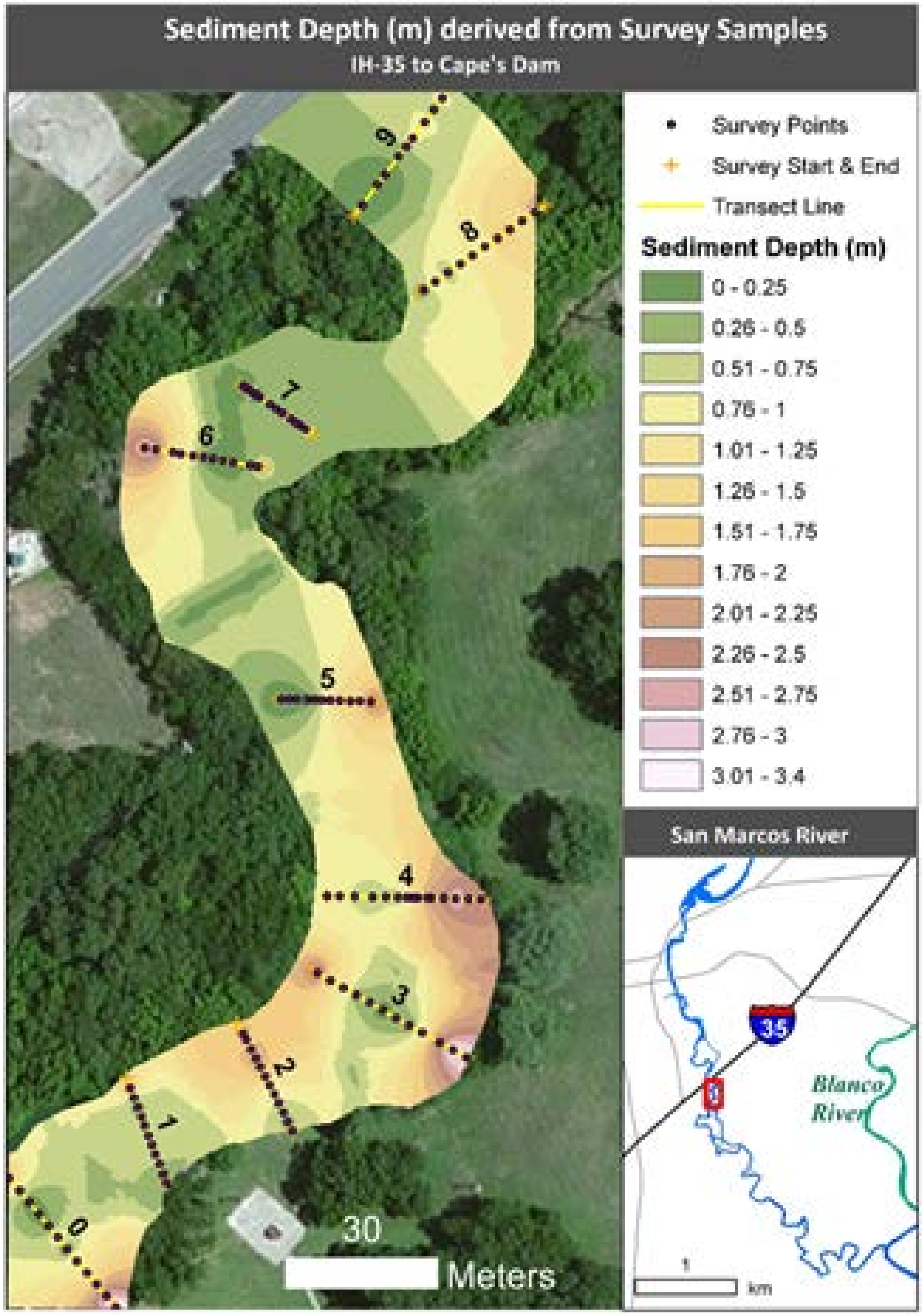


Figure 8. Location of field measurements of sediment cross-sections behind Cape's Dam and interpolated spatial distribution used in hydrodynamic modeling (adapted from Hudson 2012).

Figure 9. Sediment depth profiles for selection cross sections (XS numbers correspond to cross-section locations in Figure 8) behind Cape's Dam (adapted from Hudson 2012). The difference between the water depth and sediment depth lines represent the depth of accumulated sediment.

Simulated Flows

Four different steady state flows were modeled for this study; ranging from 45 to 300 cfs, (Table 3). The 45 cfs flow represents the expected minimum flow under the proposed Edwards Aquifer Habitat Conservation Plan during a repeat of the drought of record. The purpose of modeling this flow was to evaluate the expected distribution of depths within the channel to potentially guide aquatic vegetation restoration in this section of the river. This flow rate represents the lowest observed daily flow during the drought of record. The 100 cfs flow was chosen because it is equaled or exceeded ~90 percent of the time for the period of recorded flows within the San Marcos River (October 1, 1994 to October 23, 2015). This was also approximately the lowest summer and fall flow observed during the drought period in 2009. The 173 cfs flow was chosen as it is approximately the long-term median discharge for the period of recorded flows within the San Marcos River. The median flow represents the flow rate where half of all observed flows are higher and half of all observed flows are lower. The 300 cfs discharge was utilized to evolve the river bed topography under sediment transport conditions (high flow periods) and is equaled or exceeded approximately 10 percent of the time.

Table 3. Modeled discharge and percent of time exceeded for the San Marcos River.

Discharge Cfs[1]	Discharge Cms[2]	Percentage of time flow equaled or exceed * (1995-2011)
45	1.27	Not Determined
100	2.83	90
173	4.9	50
300	8.5	10

* Flows Measured at USGS Gage 08170500 San Marcos River at San Marcos, Texas
1 = cubic feet per second
2 = cubic meters per second

Hydraulic Modeling

Adaptive Hydraulics (ADH) is an unstructured finite element computer software package capable of modeling 2-dimensional and 3-dimensional shallow water equations, 3-dimensional Navier Stokes equations, groundwater equations and groundwater-surface water interaction. ADH solves the hydraulic and sediment transport equations while dynamically adapting the mesh so that a coarse mesh can give results as accurate as a mesh with finer resolution. (Berger et al., 2011) (See Figure 10).

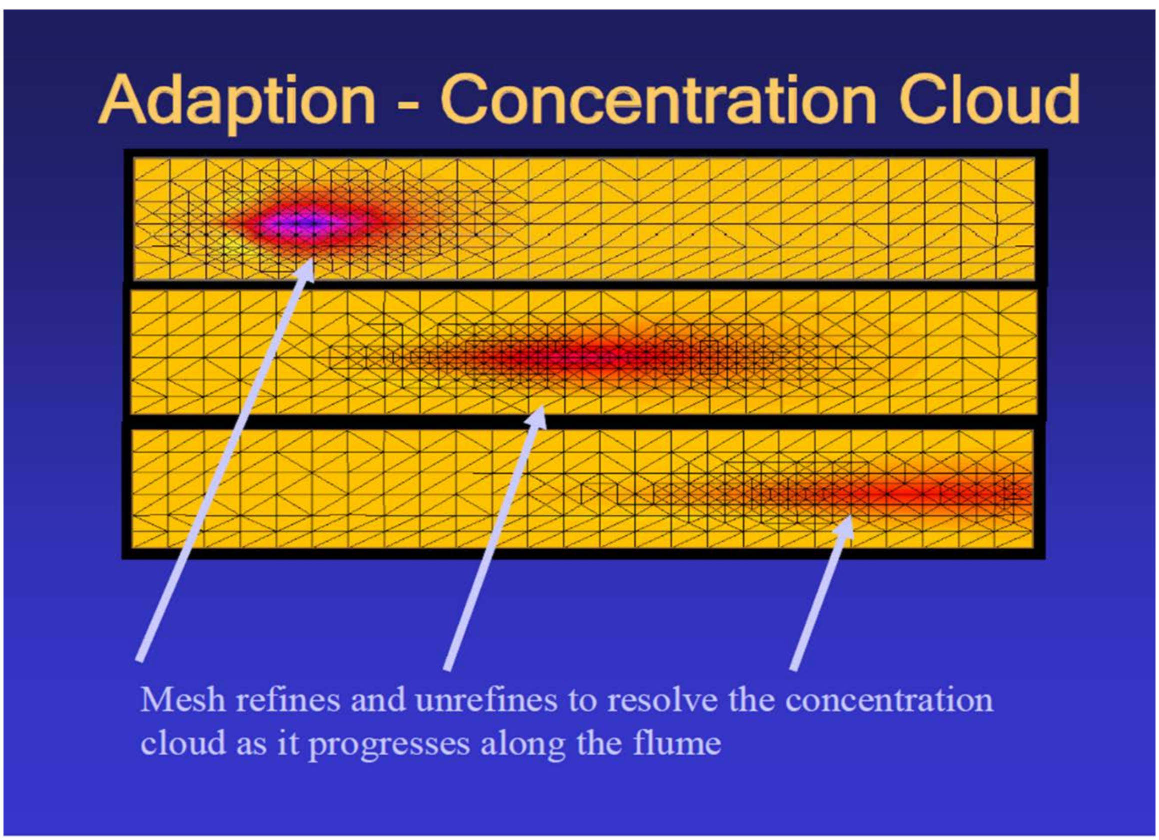


Figure 10. Example of dynamically adaptive mesh of ADH for refinement of sediment transport. The three panels show how the mesh characteristics change over time (top, middle, bottom panels) as the sediment plume moves downstream (left to right).

ADH contains other essential features such as wetting and drying, and completely coupled cohesive and non-cohesive sediment transport. One of the major benefits of ADH is it also allows for the rapid convergence of flows to steady state solutions using parallel processing architecture. ADH contains other essential features such as completely coupled sediment transport. The User's Manual for Adaptive Hydraulics Modeling system provides additional information on the hydrodynamic modeling capabilities of ADH (Berger et al., 2011).

The 300 cfs flow was modeled for 30 days to approximate bed evolution under high flow conditions where sediment transport and scouring are known to occur. This is a pragmatic modeling approach used in standard engineering practice to approximate expected long-term channel adjustments associated with intermittent 'storm events' by using a shorter simulation period with a sustained high flow given the intensive computational burden of the model. However, this is also representative of naturally occurring conditions in the San Marcos River. For example, in 2015, between May 28 and August 3, discharge in the river continuously exceeded 300 cfs for 68 days, and peak storm discharges during a single day exceed 1000 cfs every few years. Simulations were carried out on a 64 node parallel processing architecture and each 30-day simulation required approximately 23 hours of computational time to reach convergence of modeling results. Hydraulic model calibrations followed standard engineering practice by changing model parameters such as roughness and viscosity until convergence in the simulations were achieved to derive the expected bed topography and expected water surface elevation profiles for each dam scenario.

Modeling Texas wild rice, Fountain Darters and Recreation

Both Texas wild rice and fountain darters were modeled by computing physical habitat based on habitat suitability curves for depth, velocity, and substrate/vegetation cover using the approach in Hardy et al. (2012). At each computational node, given the simulated depth (d), velocity (cv), and substrate/vegetation type (sub), the suitability (S) of the 'cell' was computed by the following equations:

Texas Wild Rice and Fountain Darters

The combined suitability for Texas wild rice (TWR) was derived as the geometric mean of the component suitability's for depth and current velocity as follows:

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

The combined suitability for fountain darters (FD) was derived as the geometric mean of the component suitability's for depth, velocity and substrate/vegetation as follows:

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

The suitable area of the computational cell is then derived by multiplying the combined suitability by the area of the computational cell. The total suitable area for the reach at a given discharge is the sum of all computational cells weighted by the corresponding combined suitability in each cell. For example, if the combined suitability for depth and velocity in all computational cells for TWR were 1.0 then the amount of habitat for TWR would be equal to the surface area of the stream at that simulated discharge. For a given flow rate and dam scenario (i.e., full height, half height, or full removal), the total available habitat area for TWR or fountain darters were normalized by the total wetted surface area in the river at that simulated flow. The impacts to aquatic vegetation growth potential (including TWR) due to light attenuation from suspended sediments and other factors were incorporated into the assessment by adjusting the suitability of depths under full height, half height and full dam removal as discussed below.

Recreation

Based on a review of the recreational literature (e.g., Mosley 1983; Shelby et al., 1992) and empirical experience, a simple 2 foot minimum depth was set as the criteria to permit water borne recreation in terms of kayaks, canoes, paddle boards, and tubing. Specifically, all locations that were over two feet deep were considered suitable for recreation. Therefore, the total area suitable for recreation is the total surface area of the stream at a given flow rate and dam scenario that is over two feet deep. As was the case for TWR and fountain darters, the recreational area was normalized by the total surface area at the specific flow rate/dam scenario evaluated.

Results and Discussion

Channel Changes

Removal of Cape's Dam will result in reestablishment of normal depths equivalent to depths currently observed upstream of the backwater section and the channel below the confluence with the Mill Race return flows.

Figure 11 shows the estimated bed elevation differences between full height conditions (~ existing conditions) and the channel after bed evolution with dam removal. As noted in the figure, areas in which the bed evolution were computed to be less than 0.1 meters (~ 4 inches) are not shown as this amount of change is considered within the computational noise of the hydrodynamic model. Clearly, scour of the main thalweg (deepest part of the channel) will occur through sections with increased gradient due to removal of the backwater effect of Cape's Dam in conjunction with movement of fine sediment downstream (compare with Figures 8 and 9). Also, as expected, there is very little area in the modeled reach where sediment deposition occurs because sediments are transported downriver due to increased velocity and stream gradient with dam removal. Furthermore, increased velocity fields under half height and no dam scenarios would favor removal of existing sediments and promote reduction in the accumulation of fine sediments directly attributed to the backwater effects of the dam (Stanley and Doyle 2003).

Figures 12, 13, and 14 show the expected depth of water at flow rates of 45, 100 and 173 cfs in the San Marcos River under full height, half height and full removal conditions. A careful examination of the depths just downstream of IH-35 (very top of figures) show there is essentially no change in depth between any of the three scenarios at any of the flow rates, as would be expected, because this section of the river is not impacted by backwater effects from Cape's Dam, even under full height conditions. It is also evident in examination of Figure 12 that, even at the exceptional low flow of 45 cfs, the river maintains an active water course under all three dam height scenarios and as expected, deeper sections (holes or pools) retain over 1-2 meters of depth (3-6 feet). It should be noted that this extremely low flow rate (45 cfs) is not expected to occur except under a repeat of the drought of record and under pumping restrictions imposed on the Edward Aquifer by the EA Habitat Conservation Plan.

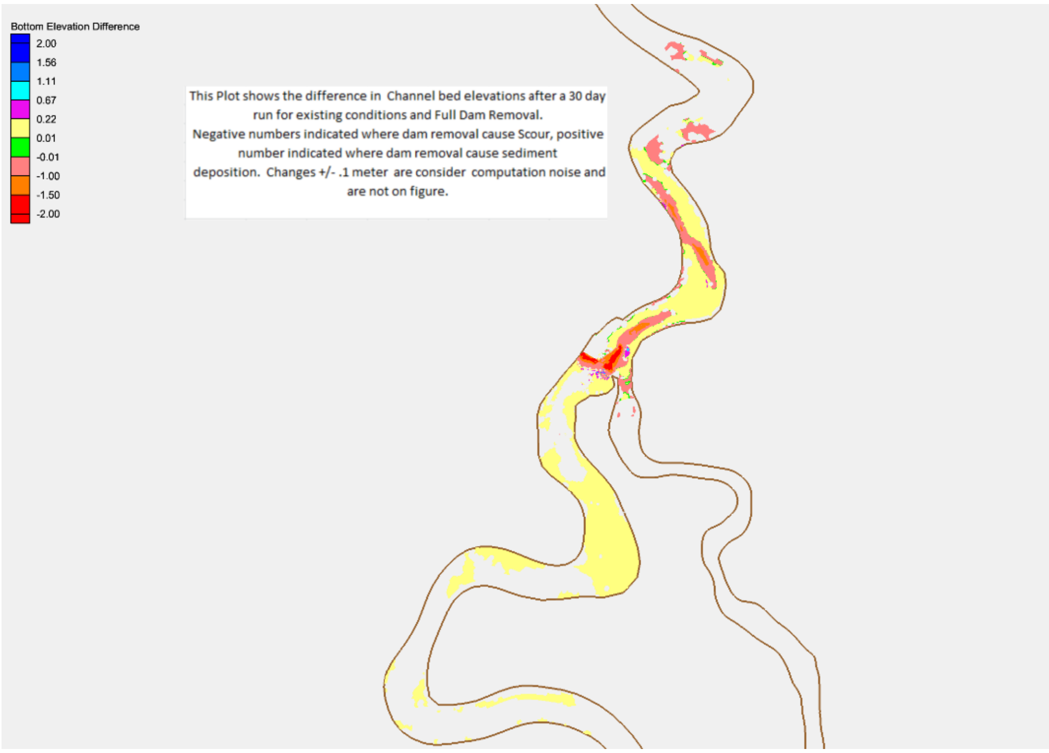


Figure 11. Changes in bed elevation difference (meters) between existing (full height) and full dam removal after bed evolution. Changes are the result of sediment being mobilized and transported downstream as velocities increase.

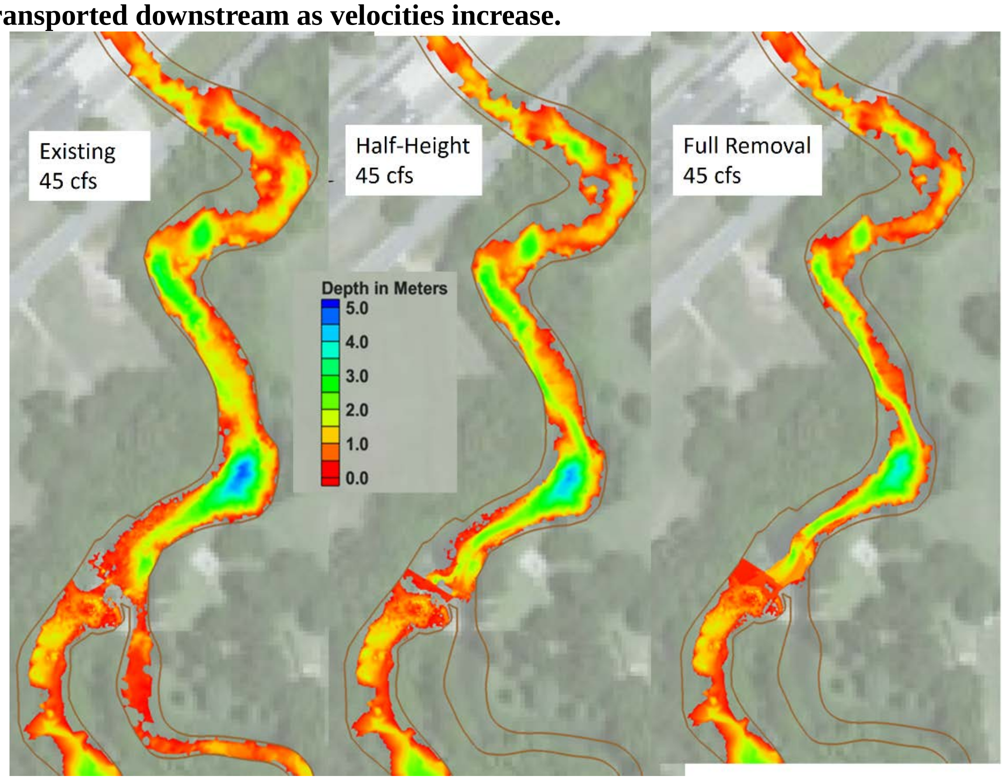


Figure 12. San Marcos River depth with full height, half height, and full Cape's Dam removal at 45 cfs (approximately the lowest single observed daily flow during the drought of record).

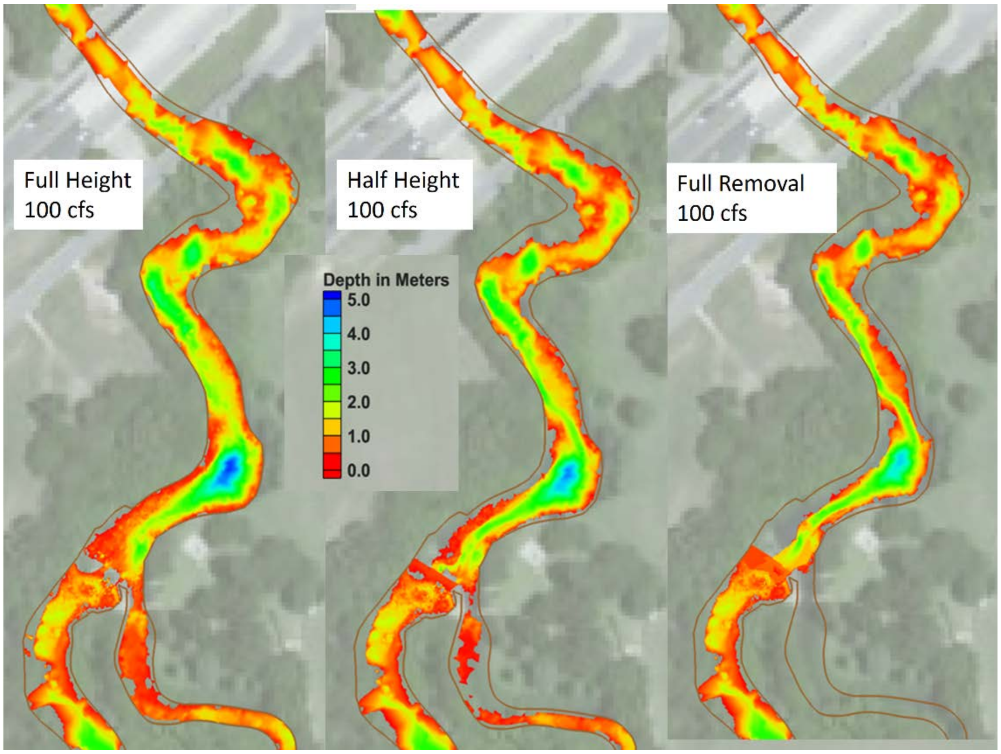


Figure 13. San Marcos River depths with full height, half height, and full Cape's Dam removal at 100 cfs (a flow equaled or exceeded approximately 90 percent of the time on a daily basis).

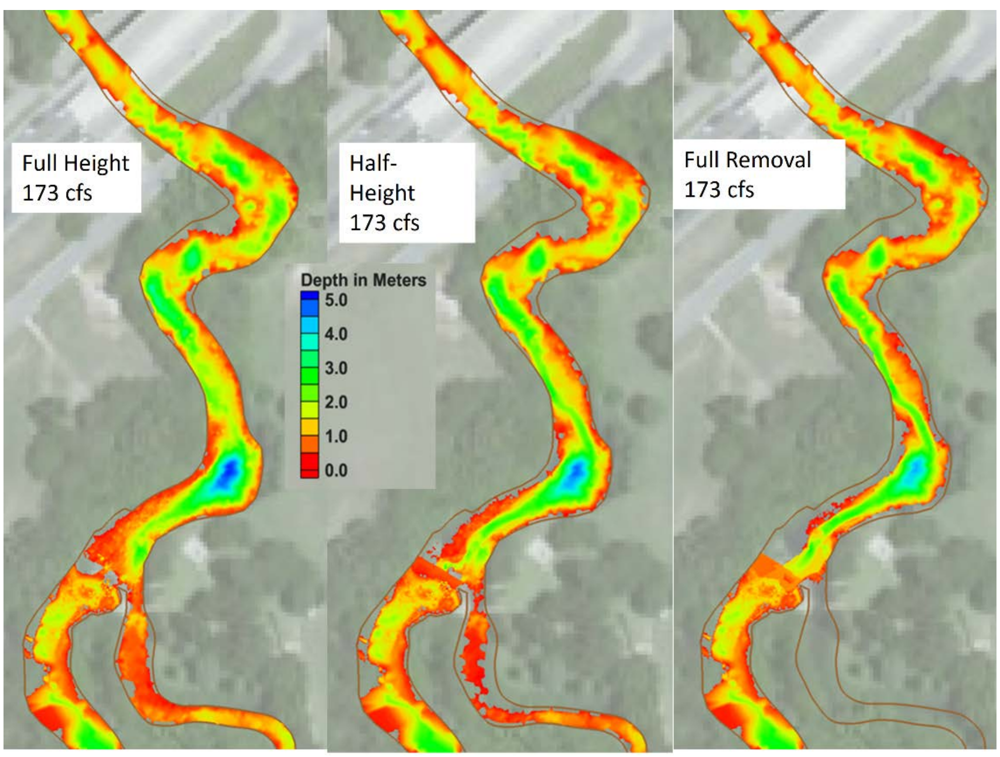


Figure 14. San Marcos River depths with full height, half height, and full Cape's Dam removal at 173 cfs (approximately the median daily flow).

The modeling results at 100 and 173 cfs clearly show that an active stream course is maintained under the dam removal scenario and even at daily flow rates equaled or exceeded over 90 percent of the time (100 cfs) that the deep pools at the bend downstream of IH-35 and above Cape's Dam maintain depth in excess of ~ 2-3 -meters (6 to 9 feet) and the remaining sections of the river are at or over a meter of depth (3.2 feet) and resemble channel depths upstream of the backwater effects of Cape's Dam. This is clearly understood from examination of Figure 15.

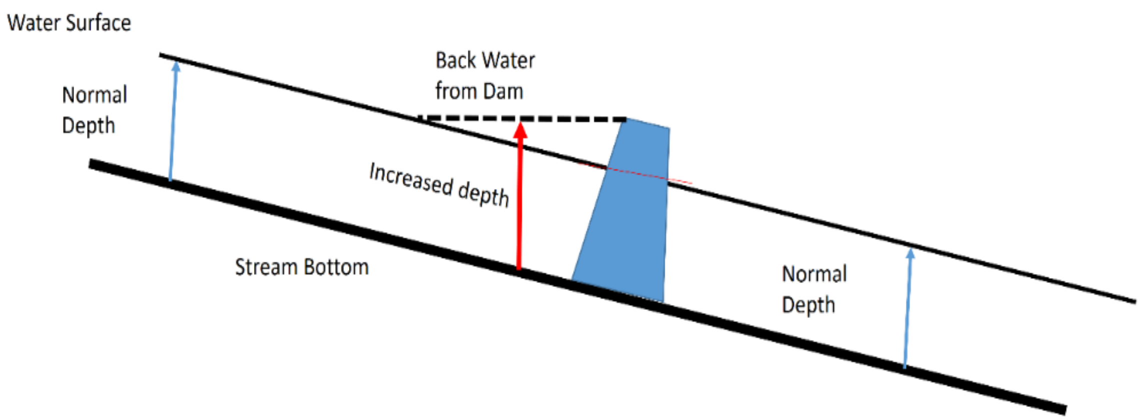


Figure 15. Normal depths upstream, backwater effects of a dam, and normal depths downstream in an idealized channel.

Upstream of any backwater effects from a dam, the water surface elevation assume normal depth (left side of figure). Normal depth also occurs downstream past the short influence of the flow over the dam (right side of figure). Placement of a dam creates a backwater effect where the water surface is flat in the upstream direction until it intersects with the slope of the natural stream surface at the elevation of the dam upstream (middle of figure). Obviously, the higher the dam, the greater the distance in the upstream direction of the backwater effect. Removing the dam results in reconnecting the energy grade line and the section of the river where the dam produced the backwater effect reverts to the normal depth. This is precisely the results illustrated in Figures 12, 13 and 14 under any range of flow rates in the river in the reach impacted by the backwater from Cape's Dam. Compare depths at the upper left of these figures with the sections of river under the backwater section with the dam (middle sections), and areas downstream of the dam location (bottom). Without the dam, the channel will revert to depths and morphologies that are very similar to those found in the existing un-dammed sections of the San Marcos River.

The results for both 100 and 173 cfs clearly show that reductions in stream width associated with dam removal are primarily localized to the section immediately above Cape's Dam (i.e., the backwater section). This is expected because the current widths are partly the result of impoundment, and the impounded area will not exist with dam removal. The total reduction in stream area with half height and full Removal is 15 and 17 percent, and are primarily a result of reduced or elimination of flows in the Mill Race. A careful comparison of the channel widths between the different dam removal scenarios and flow rates illustrate that dam removal will not result in extensive areas of exposed banks or result in the river corridor becoming a mud pit. Reduction in stream width at 45 cfs will be extensive under any dam scenario. The reader is reminded that 45 cfs is an extremely low flow that has been recorded only for a single day during the entire period of hydrologic record.

Hudson (2012) monitored geomorphic adjustments of the San Marcos River downstream of Cape's Dam after channel dredging to remove the invasive aquatic plant *Cryptocoryne beckettii*. Study results showed that the river channel remained stable with no evidence to support either head cutting, lateral channel migration, or significant back sloughing. This is due to the cohesive nature of the natural bank materials. These results are applicable to the section of river impacted by Cape's Dam and similar results are expected (i.e., lack of bank erosion or lateral scour) with dam removal.

Implications on Flows in the Mill Race

<u>Reduction in Cape's Dam to half height will result in a reduction of the amount of time that flows will enter the Mill Race. Under full removal flows will only occur at flow rates equaled or exceeded about 10-15 percent of the time.</u>

The simulation results for half height and full removal shown in Figures 12 through 14 clearly demonstrate that reduction in the height of Cape's Dam or its removal will impact how often water will flow into the Mill Race. As a validation check on the physical representation of the model, the actual bed elevations in the river immediately upstream from Cape's Dam and the entrance to the Mill Race were surveyed on Tuesday July 21st, 2015. The cross section profiles of the San Marcos River and the Mill Race showing the observed water surface elevation and depth of the their respective channel bottoms are shown in Figure 16. These cross sections were obtained using a common bench mark so the elevations are shown to same absolute scale. These data show that under existing (or full height) conditions, the difference in the elevation at the bottom entrance of the Mill Race and the San Marcos River is approximately 3.9 feet and in excellent agreement with the physical representation of the computational mesh used in the Cape's Dam modeling scenarios.

This difference in elevation between the river and elevation of the bottom entrance to the Mill Race dictates when and to what extent water will flow between the San Marcos River and Mill Race as a function of total flow in the San Marcos River under the various dam configurations. This is easily illustrated by the relationship between stage (height of the water or depth of river flow) and discharge under full height, half-height, and full Cape's Dam removal (Figure 17). Full height conditions in Figure 17 were derived from empirical measurements used in the initial calibration of the hydrodynamic model while the relationships between water surface elevation and discharge for the half height and full dam removal are derived from the simulation results after bed evolution.

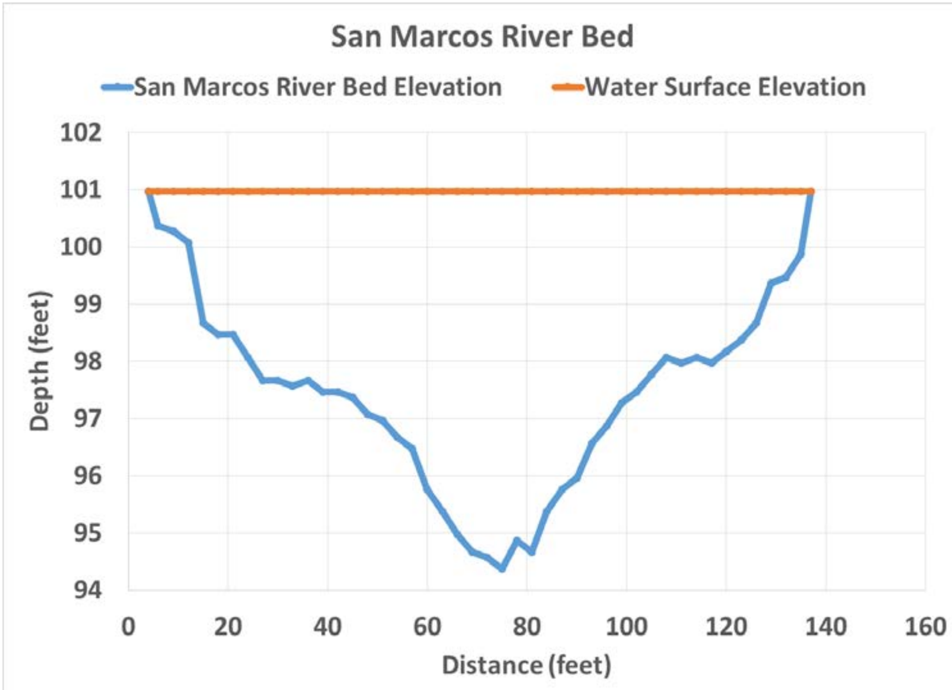
Figure 17 illustrates clearly that, under full height conditions, Cape's Dam increases the water surface elevation above the dam and flows enter the Mill Race over a wide range of discharges (this was the original intent of constructing the dam and mill race). This is reflected in the simulation results presented in Figures 12 through 14. Under half heightconditions, where the height of the water backed up behind Cape's Dam would be lower, water would not enter the Mill Race until the San Marcos River discharge was approximately 130 cfs. This flow rate is equaled or exceeded approximately 53 percent of the time based on the daily flow record in the San Marcos River. Conversely, flows would not enter the Mill Race approximately 47 percent of the time, or when flows were less than about 130 cfs. Under full dam removal, water would enter the Mill Race when San Marcos flows are approximately equal to or higher than 280 cfs. This average daily flow rate is equaled or exceeded only about ~10-12 percent of the time. It should be noted that daily flows of this magnitude and greater are rarely sustained over long periods but are generally associated with short-term flood events.

These results suggest that if Cape's Dam is rebuilt at half height or fully removed, the Mill Race will remain dry or contain stagnant water for extended periods of time between short duration flood events. Even at higher discharges under full height (existing) conditions (e.g., > 250 cfs), water quality impacts due to the backwater effects and flow into the Mill Race are observable. For example, empirical data collected on September 28, 2015 in mid-morning (9:30 – 10:15) prior to extensive recreation use in upstream river reaches showed increasing turbidity (suspended sediment) between Cheatham Street (0.18 FTUs), immediately above Cape's Dam (0.51 FTUs) and at the end of the Mill Race (2.28 FTUs). Dissolved oxygen in the Mill Race was also lower (7.0 ppm) compared to 8.0 in the main river.

<u>Diversion of flows into the Mill Race will continue to reduce the quantity and quality of aquatic habitats in the main stem San Marcos River which are already stressed during low-flow periods.</u>

It is intuitive that, as the total flow of the San Marcos River decreases, splitting the flow (i.e., diversion of flow into the Mill Race) will result in increasingly lower depths per unit discharge in the main steam San Marcos River below the Cape's Dam under half height or full removal. The greatest ecological protection for the aquatic community, especially for the listed species in this section of the river is to retain all the flow of the San Marcos River within its historic natural channel.

The presence of the Mill Race does not offered any added protection against flooding within the San Marcos River in this section of the river, as the height of the water surface elevation is artificially raised by the presence of Cape's Dam. With dam removal, the channel capacity of the San Marcos River will be increased with resulting lower water surface elevations.



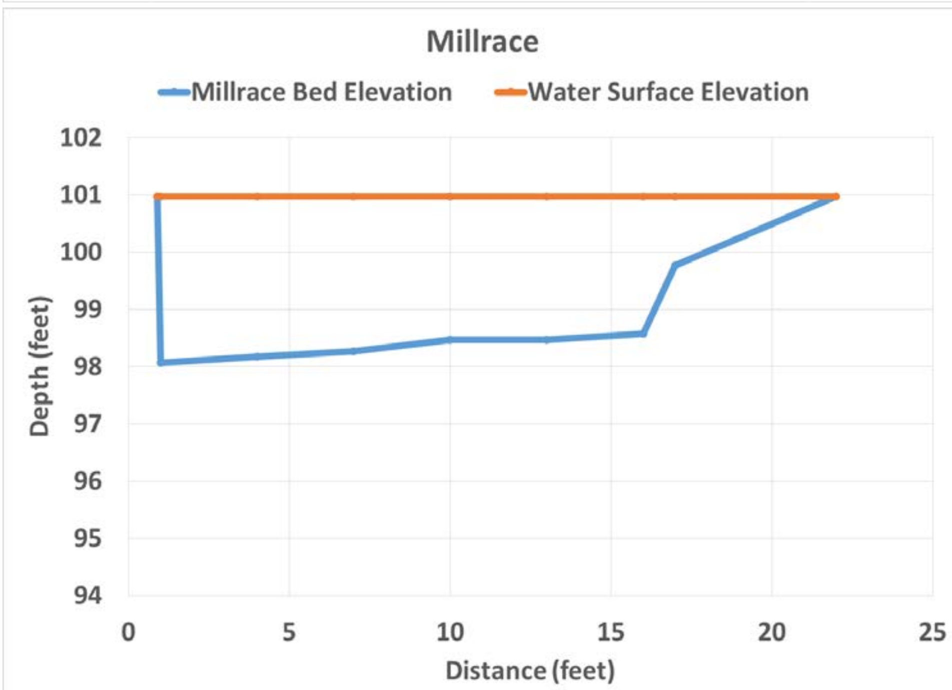


Figure 16. Computational mesh (upper left), location of physical measurements (upper right), cross section profile of the San Marcos River above Cape's Dam (lower left) and cross section profile of the Mill Race (lower right).

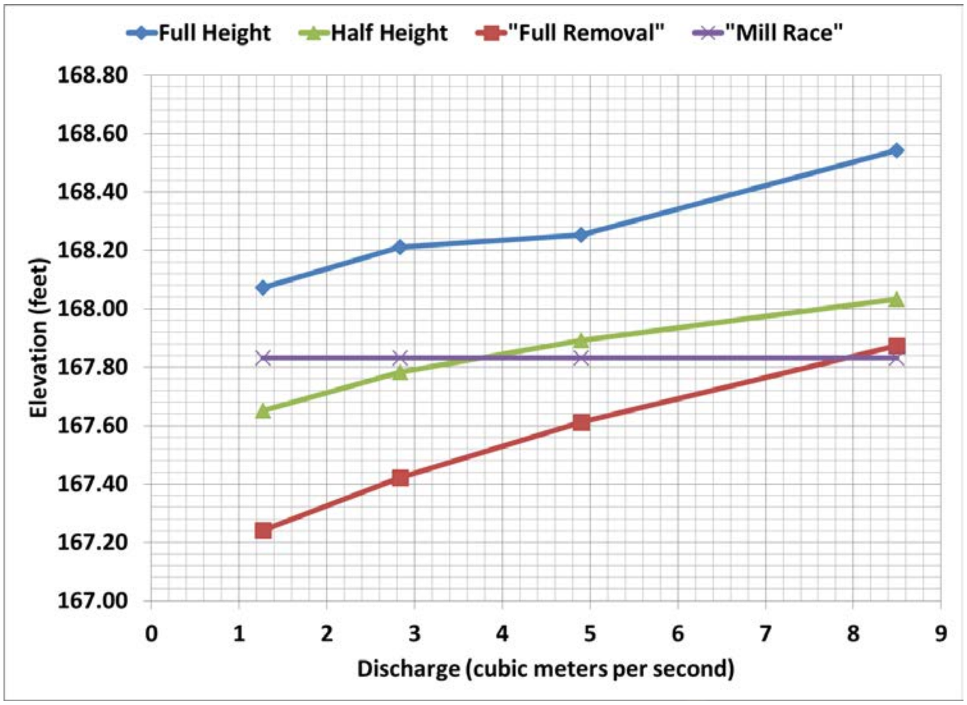


Figure 17. Relationship between water surface elevation and discharge for existing (full height), half height and full Cape's Dam removal and the bed elevation of the inlet to the Mill Race. Whenever points are above the 'Mill Race' line, this indicates that some amount of flow from the San Marcos River will be diverted into the Mill Race channel

Texas Wild Rice

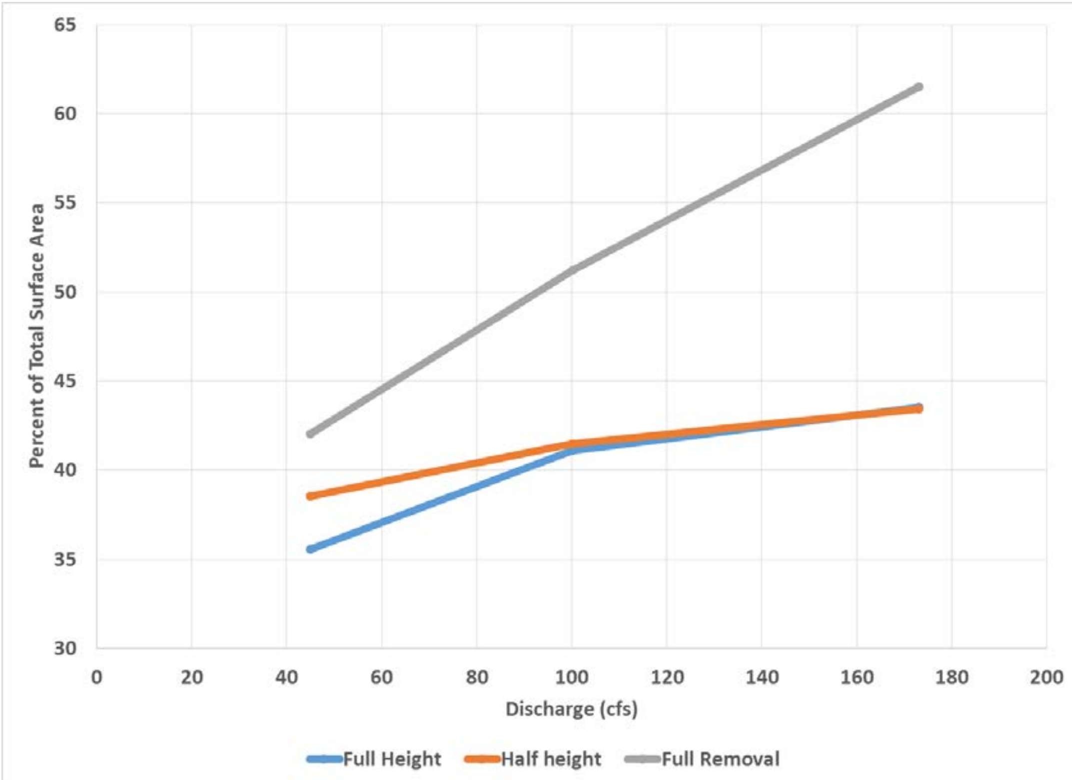
Removal of Cape's Dam represents the best ecological benefits to improving habitat for Texas wild rice.

Figure 18 (top half) shows the amount of Texas wild rice habitat as a percent of the total stream area under full height, half height and full removal and the associated percent change compared to full height conditions (bottom half) for each simulated flow. It is clear that removal of Cape's Dam provides the greatest potential benefit to TWR compared to any with dam scenario over any simulated flow rate. This increase in TWR habitat is also indicative of expected benefits to other native aquatic vegetation. These results likely underestimate the actual increase in habitat quantity and quality with dam removal due to a variety of physical and life history factors of aquatic vegetation not incorporated into the modeling as discussed below. The expected improvement to habitat conditions with dam removal is also based on multiple years of TWR restoration efforts within the San Marcos River by the Meadows Center for Water and the Environment in which applied research and restoration actions have significantly increased the aerial coverage of TWR.

Photosynthetically Active Radiation (PAR)

The decrease in depths within the existing backwater section of the river with removal of Cape's Dam will result in an increase in available PAR reaching the stream bottom which will promote increased TWR and other aquatic macrophyte growth in this section of the river.

Given no nutrient or CO_2 limitations, aquatic macrophyte growth is directly dependent on light availability in terms of Photosynthetically Active Radiation (PAR) reaching the stream bottom. PAR naturally attenuates with water depth, however, PAR reductions due to suspended sediments or other particulate and dissolved matter greatly increases light attenuation and therefore inhibits aquatic plant growth (e.g., Pedersen et al., 2013; Middleboe and Markager 1997; Kemp et al., 2004). Figure 19 shows PAR readings as a function of water depth taken in Spring Lake and immediately upstream of Cape's Dam during a low-recreation weekday morning (9:30-10:15) in September of 2015. The data clearly demonstrate that, relative to Spring Lake, there is a reduction in PAR at each depth upstream of Cape's.. Current research from the San Marcos River clearly shows a strong relationship between increasing reductions in PAR with water depth longitudinally downstream from Spring Lake Dam (Bryne 2015). Under non-stormwater conditions, the reduction in PAR and increased turbidity above Cape's Dam is directly attributed to suspended sediment due to water recreation density. These findings are based on 15 minute turbidity readings at three longitudinal locations between Sewell Park and upstream of Cape's Dam with concurrent hourly recreation counts in Sewell Park, City Park, and Rio Vista since 2012 (Hardy, unpublished data). This reduction in PAR is in part contributing to the observed reduction in the amount of stream bed coverage by aquatic macrophytes in the backwater reaches above Rio Vista and Cape's Dam (San Marcos Observing System and Meadows Center for Water and Environment vegetation monitoring data since 2009). Ongoing research with TWR to quantitatively document the response of plant growth in terms of above- and below-ground biomass relative to suspended sediment and PAR in the San Marcos River supports these relationships (Crawford 2016).



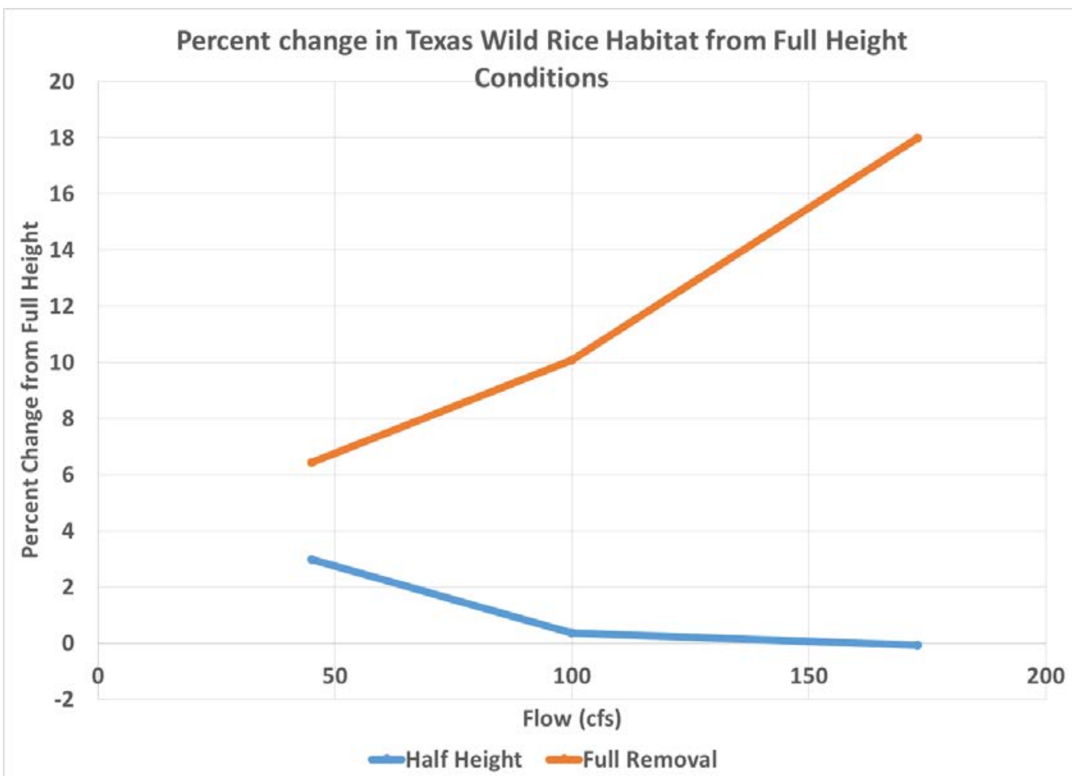


Figure 18. Percent of total surface area and percent change in Texas wild rice habitat compared to full height conditions.

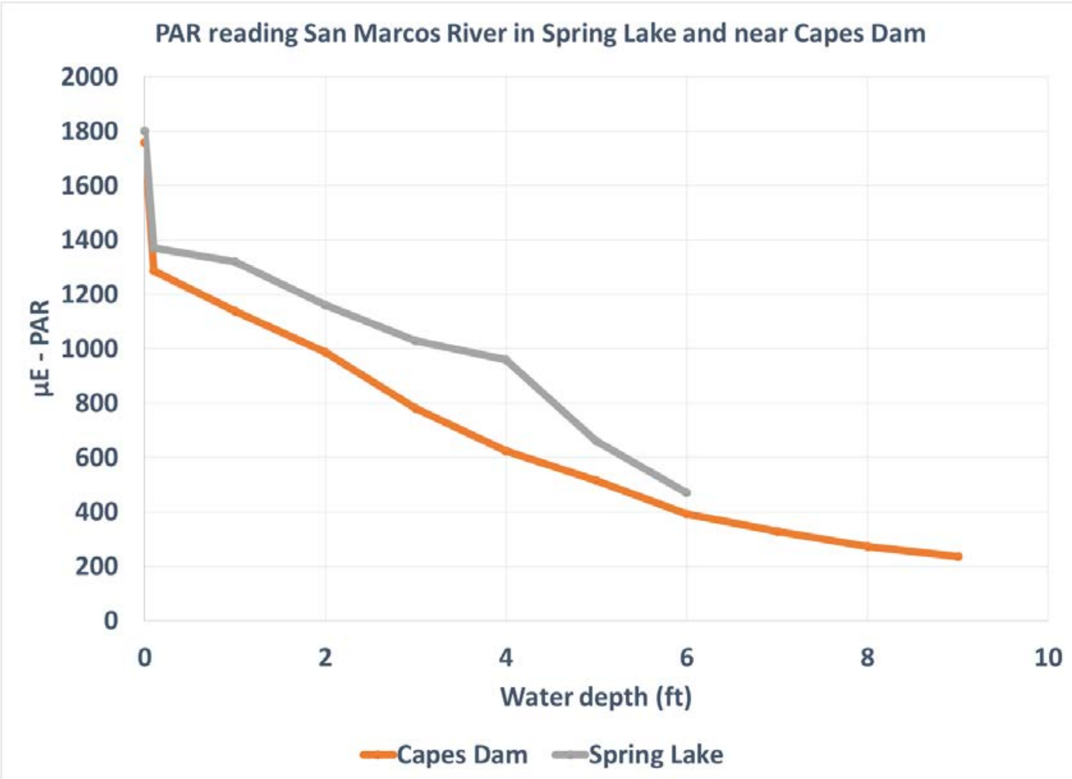


Figure 19. PAR reduction with depth in Spring Lake compared to upstream of Cape's Dam.

Velocity and Gas Exchange Dynamics in Aquatic Plants

Increased distribution of higher velocities in the backwater section of the river with dam removal will promote higher growth rates of TWR and other aquatic macrophytes.

The following is taken from Pedersen et al. (2013):

The 10^4-fold lower diffusion coefficient of gases in water, compared with in air, presents a major challenge to submerged plants (Armstrong, 1979; Maberly and Madsen, 2002). Diffusive boundary layers (DBL) develop on all surfaces and their thickness adjacent to leaves in water is of the same order of magnitude as those for leaves in air (Vogel, 1994; Raven and Hurd, 2012). Although the transport distance for gases across the DBL is similar, the much lower diffusion coefficient in water results in a 10^4-fold lower flux for the same concentration gradient and thus the DBL constitutes a much larger proportion of the total resistance to gas exchange for leaves under water than in air (Maberly and Madsen, 2002). The "bottleneck effect" of the DBL on underwater gas exchange was demonstrated in a study of four submerged aquatic species, where the DBL accounted for 90% of the total resistance to carbon fixation (Black et al., 1981).

Basically this means that exchange of gases and nutrients between the water and the leaf is more difficult for aquatic plants due the mechanics of the diffusion process in water. Aquatic plants, such as Texas wild rice have adapted strategies however to overcome these limitations. Increased water velocities at the leaf surface have been shown to increase the photosynthetic rates in several aquatic macrophytes due to reduction in the thickness of the DBL (Black et al., 1981). Powers (1996) demonstrated that for TWR the stem density was greater in fast flowing water (0.40-0.49 m/s) than in either moderate (0.12-0.24 m/s) or slow flowing (0.05-0.12 m/s) water. Hardy et al. (2015) harvested thousands of free floating TWR tillers from the San Marcos River and showed > 90% success rate for propagation of TWR exposed to moderate velocities. This research also showed increased mortality of TWR when raised in still water conditions. Hardy et al. (2015) utilized hydraulic and habitat modeling imposing suitable depth and moderate velocities to identify targeted areas for removal of nonnative aquatic plant species and replacement-planting of TWR in the San Marcos River. Utilization of hydraulic and habitat modeling to identify suitable areas for TWR was shown to be highly successful. All treatment areas in which the non-native species *Hydrilla* or *Hygrophila* were removed, and TWR was planted in suitable velocity conditions, showed net gains for TWR. System-wide increases in TWR was on the order of greater than 300 m^2. Modeling results based on suitable depth and velocities to guide removal of nonnative aquatic species and planting of other native aquatic species (i.e., *Sagittaria* sp., *Ludwidia* sp., and *Potamogeton* sp.) was also highly successful.

Implications on Reproduction and Genetic Integrity

Reduction of depths with removal of Cape's Dam will provide an increase in areas suitable for sexual reproduction of TWR important for maintenance of genetic integrity of the population.

TWR propagates by both sexual and asexual means. Asexual propagation occurs from the production of tillers that represent a clone of the host plant that expands or detaches and becomes established in new locations. Sexual reproduction occurs when the plant reaches the surface and relies on wind based pollination to produce seeds that subsequently disperse. Depths over approximately 2 meters (~6 feet) result in TWR rarely reaching the surface and using the sexual reproduction strategy.
Both types of reproduction are important to the long term genetic viability of the species in the San Marcos River. The San Marcos Aquatic Resource Center (USFWS) has developed reintroduction guidelines for the use of tillers versus seed based propagation for plantings of TWR by river sections to ensure long term genetic integrity of the species. Reduction in depths in the backwater section of Cape's Dam with dam removal provides increased diversity of depth conditions that will support both tiller based expansion as well as sexual reproduction by allowing proportionally greater access by TWR to suitable habitats.

Fountain Darters

Habitat Quantity

Removal of Cape's Dam will provide an increase in the area of fountain darter habitat due to both improved hydraulic conditions (i.e., depth and velocity) as well as aquatic macrophyte expansion.

The amount of fountain darter habitat based only on depth and velocity for each flow rate and dam scenario is provided in Figure 20 as a function of total stream area. As noted previously, the total surface area is reduced by ~ 15-17 percent due to small losses along the stream margins in the backwater section of the channel above Cape's Dam and primarily from lack of flows in the Mill Race. The results however, indicate that the quantity of darter habitat as a function of total stream area is highest under dam removal for all stream flows. It should be noted that the increases in habitat for both half height and full dam removal are underestimated since these results do not reflect expected increases in darter habitat due to increases in the density and distribution of aquatic macrophytes.

Long term monitoring has clearly shown that darter densities are higher in aquatic vegetation compared to open substrates (Biowest 210a, b). As noted above, the reduction of depths and increased PAR reaching the stream bottom with dam removal is expected to increase the distribution and abundance of aquatic macrophytes in this section of river, hence improving overall fountain darter habitat. Modeling the expansion of aquatic vegetation under either half height or full dam removal was beyond the scope of this work.

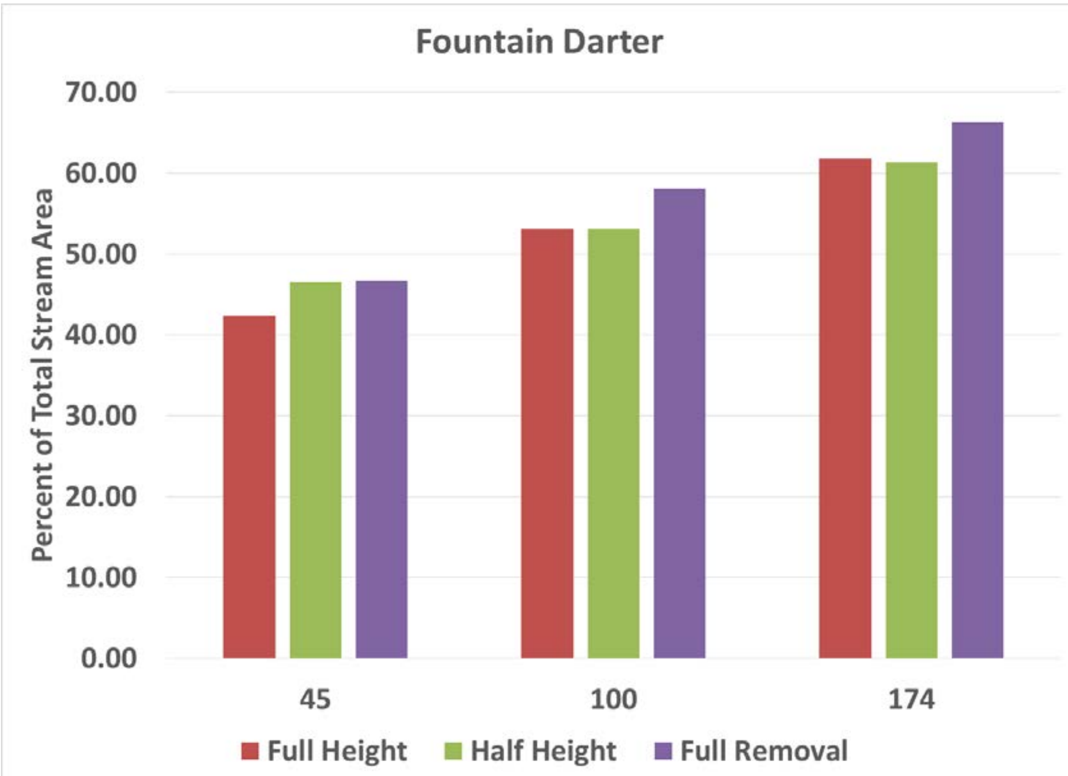


Figure 20. Percent of total stream area suitable for fountain darters under full height, half height and full dam removal.

<u>Habitat Quality</u>

<u>Removal of Cape's Dam will provide an increase in the quality of fountain darter habitat over all flow ranges compared to full height or half height dam scenarios.</u>

Figures 21 through 23 show the number of computational cells containing combined suitability values between 0.1 and 1.0, where a combined suitability of 0.1 is considered 'poor' habitat while a combined suitability of 1.0 is considered 'ideal'. These combined suitability values reflect the individual suitability associated with depth and velocity at each location (computational cell) and provide an objective comparison of potential habitat quality across difference flow ranges under full height, half height and full dam removal.

These results clearly show that stream conditions under dam removal provides a significant increase in the overall number of spatial locations (i.e., computational cells) containing higher suitability values compared to full height or half height conditions.

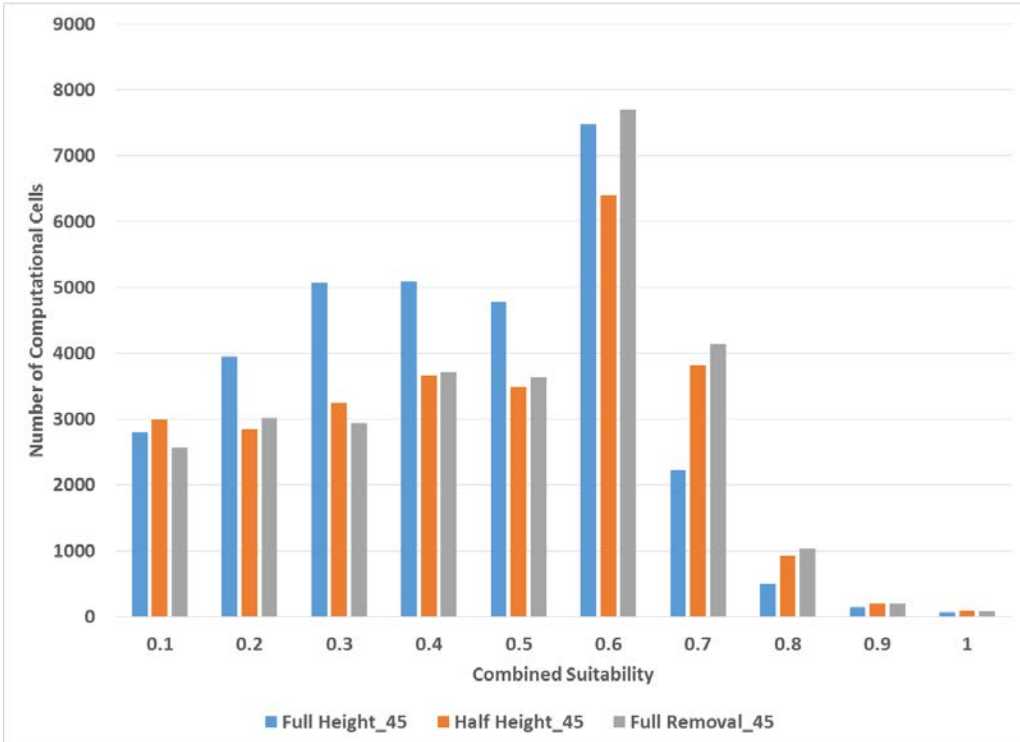


Figure 21. Fountain darter habitat quality under full height, half height and full dam removal at 45 cfs.

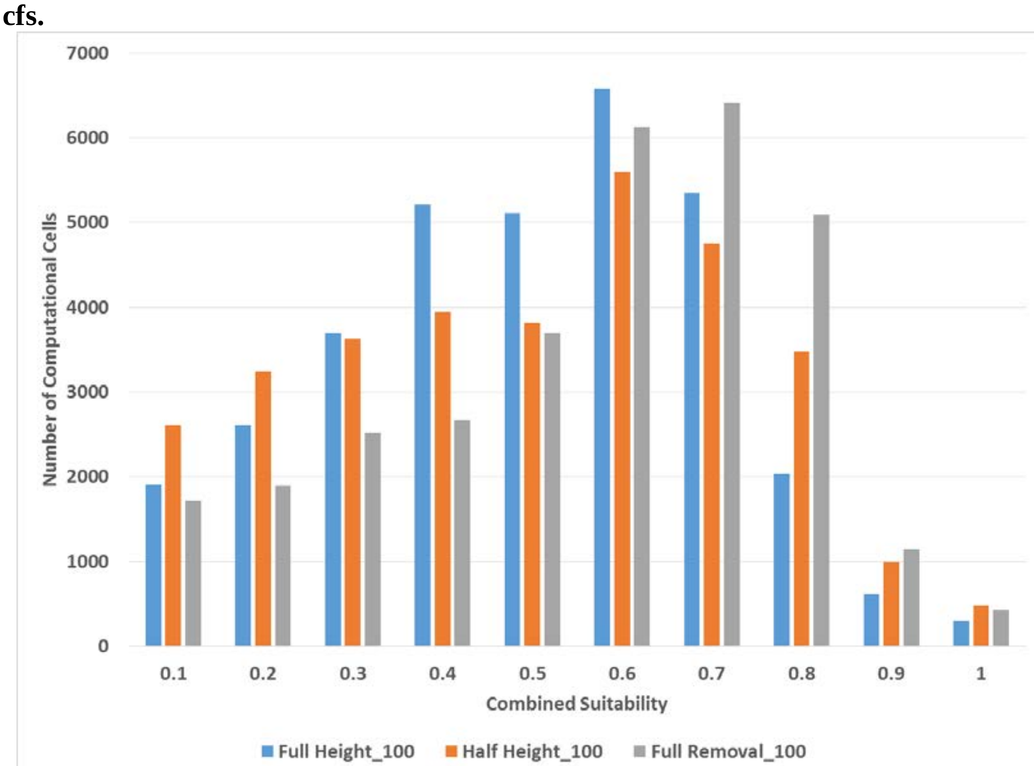


Figure 22. Fountain darter habitat quality under full height, half height and full dam removal at 100 cfs.

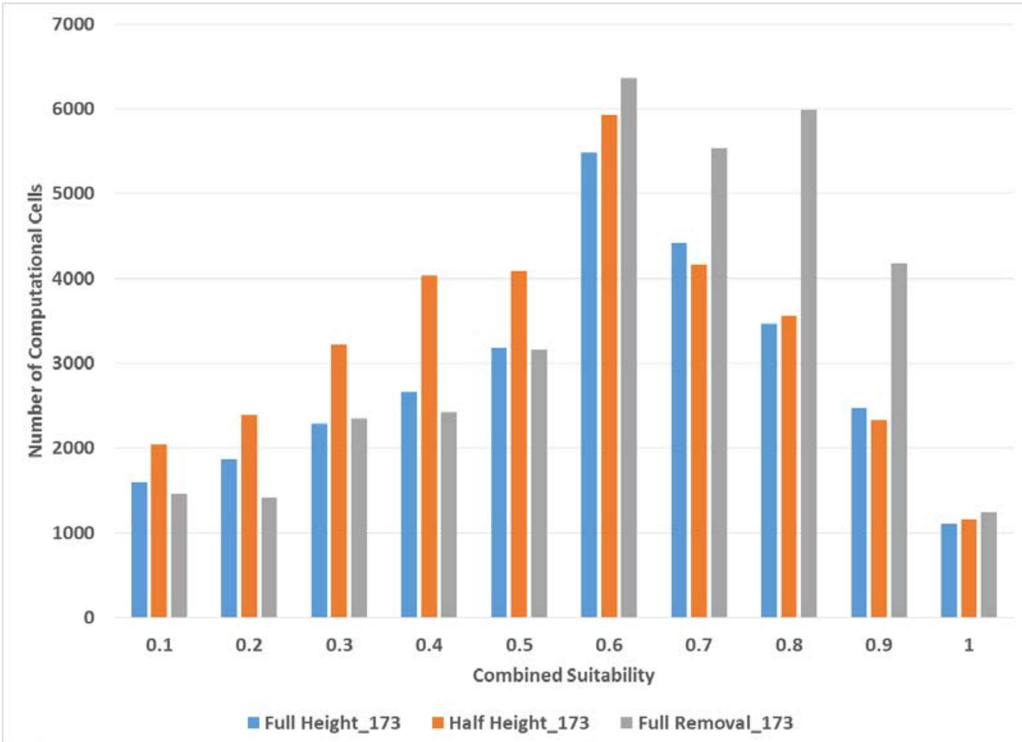


Figure 23. Fountain darter habitat quality under full height, half height and full dam removal at 173 cfs.

Impacts of Low Head Dams

Removal of Cape's Dam will eliminate known ecological impacts associated with low head dams such as adversely affecting warmwater stream fish, aquatic macroinvertebrates, and aquatic/riparian plants by blocking migration pathways, degrading habitat and water quality, and fragmenting the river landscape, which results in a loss of native species diversity.

Low head dams, such as Cape's Dam, are known to contribute to habitat fragmentation, lower aquatic diversity and disrupt migration pathways for fish and aquatic/riparian species. Research suggests that the effects of low head dams on fishes, aquatic macroinvertebrates, aquatic and riparian plant species and their habitats are similar to those reported for larger dams (Anderson et al., 2000; Santucci et al., 2005; Tiemann et al., 2004). Behen (2013) documented that the fish community below Cape's Dam is most closely allied with the stream fish community in the Brazos River rather than the spring fish assemblage in the upper San Marcos River. This was attributed to the impact of Cape's Dam on upstream movement of fishes. Furthermore, research has shown that fish species richness and diversity generally increase in reconnected areas after dam removal (Burroughs et al. 2010; Catalano et al. 2007; Bednarek 2001).

Recreation

Removal of Cape's Dam will provide a safe and sustainable recreation corridor that will accommodate, swimming, tubing, canoeing, kayaking and paddle boarding without a demonstrable negative impact relative to full height or half height dam scenarios for these water based recreation activities.

Figure 24 shows a comparison of changes in normalized habitat area for recreation at different simulated flow rates under each of the dam scenarios evaluated.

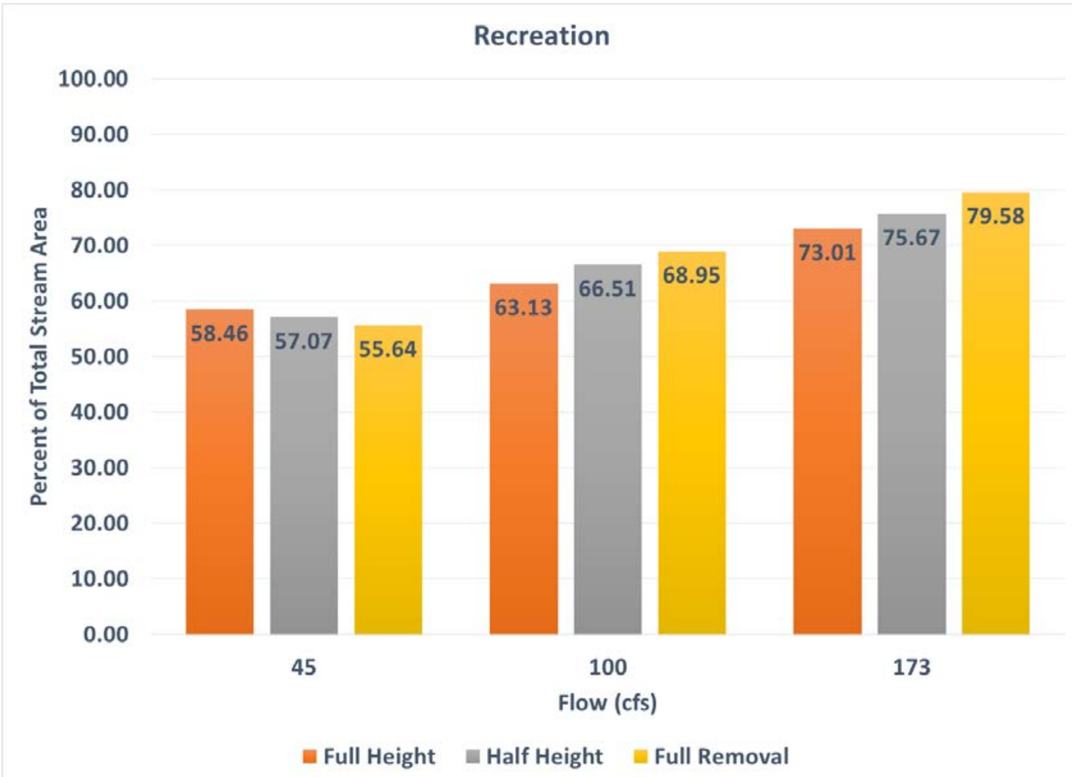


Figure 24. Area of normalized available habitat as a percent of the stream area for recreation for different flow rates and dam scenarios.

As noted previously, a careful examination of Figures 12, 13, and 14 show the expected depths of water at flow rates of 45, 100 and 173 cfs in the San Marcos River under full height, half height and full removal conditions maintain adequate areas with sufficient depths (> 2 feet) to support all forms of contact recreation throughout the river channel. The results are also clear in that with dam removal, existing deep water areas (downstream of IH35, upstream of Cape's Dam, the plunge pool below Cape's Dam and the plunge pool at the end of the Mill Race) will still exist and retain depths in excess of 4-6 feet even under flows of 100 cfs, which are equaled or exceeded 90 percent of the time on a daily basis. Removal of Cape's Dam will result in the maintenance of a safe sustainable recreation corridor with sufficient depths to support all forms of contact water recreation.

Conclusions

The modeling results and supporting science-based literature clearly demonstrate that the most ecologically beneficial conditions for the San Marcos River is removal of Cape's Dam. There are demonstrably no ecological benefits to the native aquatic or riparian fauna within the San Marcos River to reconstruct Cape's Dam at either half height or full height. The results also clearly demonstrate that Dam Removal will result in a safe and sustainable recreation corridor for all forms of contact recreation over daily flow rates that are equaled or exceeded 90 percent of the time. Dam removal will maintain river conditions similar to free flowing sections above IH35 and downstream of the Thompson Island. Under half height or full removal options, the Mill Race will have substantially less flowing water and/or reductions in the amount of time that water will flow into the Mill Race. Empirical data collected from the Mill Race shows that it currently results in degraded water quality even at flow rates that are above the long term median daily flows.

The assessment also shows that removal of Cape's Dam will result in improved conditions for restoration of aquatic macrophytes including the endangered Texas wild rice. Increased aquatic macrophytes will increase the available habitat for the endangered fountain darter in this reach of the San Marcos River. Dam removal will result in river conditions that are more favorable for meeting long term Biological Goals identified for this reach of river in the Edwards Aquifer Habitat Conservation Plan.

Rebuilding Cape's Dam to either full or half height will continue to cause fragmentation of the habitat within the San Marcos River, impede or stop migration pathways for aquatic and riparian species, and will continue to result in abnormal accumulation of fine sediments behind the dam that negatively alter fish and aquatic macroinvertebrate habitats and result in loss of native species diversity.

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Appendix A – Author Biographies

Dr. Hardy – Short Biography

Dr. Thomas Hardy holds a Ph.D. in Civil and Environmental Engineering, M.S. and B.S. degrees in Biology and a B.S. in Secondary Education. He is a tenured Full Professor in the Department of Biology at Texas State University and holds the Meadows Center for Water and the Environment (MCWE) Endowed Professorship for Environmental Flows and is the Chief Science Officer at MCWE. Dr. Hardy was a tenured Full Professor in the Department of Civil and Environmental Engineering at Utah State University where he was the Director of the Institute for Natural Systems Engineering for 21 years and the Associate Director of the Utah Water Research Laboratory for 10 years. He is a founding member and Past-President of the Ecohydraulics Section of the International Association for Hydro-Environment Engineering and Research and served on the National Academy of Science Committee on review of the Texas Instream Flow Program. Dr. Hardy's career has spanned a wide array of fundamental and applied multidisciplinary research including the development, testing, validation, and application of assessment methodologies in aquatic systems. His research includes use of unmanned autonomous vehicles for remote sensing and image processing, aquatic ecosystems modeling, aquatic vegetation and macroinvertebrate dynamics, river and reservoir water quantity modeling and distributed watershed modeling. He is also active in the evaluation of fresh water inflows on bay and estuary health and recreation based impacts to fish, aquatic macrophytes and macroinvertebrate communities. He is an internationally recognized expert in instream flow assessments and has collaborated with national instream flow and river restoration programs in the United States, Canada, Mexico, United Kingdom, western European countries, South Korea, and Japan.

Dr. Raphlet – Short Biography

Dr. Nolan Raphelt holds a Ph.D. and ME in Civil Engineering and a BS in Agricultural Engineering. He is also a licensed Professional Engineer with the State of Texas. His research and applied experience includes studies on the hydrologic regimes of Texas' rivers and streams in terms of impacts of flow alterations on stream stability and morphology, and the aquatic and riparian habitats. Dr. Raphelt has extensive experience in sediment modeling, 1-D, 2-D and 3-D hydraulic modeling; riverine erosion and sediment transport; non-cohesive sediment modeling in coastal/estuarine environments; channel sedimentation and restoration modeling; simulation in riverine and coastal flood control and navigation channels; fluvial and geomorphic analysis in riverine/coastal environments; and the effects of flow sediment diversion in riverine and estuarine areas. Dr. Rpahelt spent several decades at the US Army Corps of Engineers Coastal and Hydraulics Laboratory where he performed numerical modeling in a number of water resource areas, including 1, 2 and 3-dimensional numerical modeling of the hydrodynamic and sediment regimes in river and estuarine environments. He was responsible for the development of 2 and 3 dimensional flow and sediment models for the Mississippi River from Pool 18 on the upper Mississippi to the mouth of Mississippi River. This work included 3-D sediment modeling of the Old River Control Complex (ORCC) structures which include three major flood control structures and one hydropower plant. The work on the lower Mississippi River focused on the effects of proposed sediment diversion for wetland restoration in adjacent shallow water bays. Two of the studies, Apalachicola River and Pool 18 study involved the tracking of sediments dredged from the navigation channel and placed on riverbanks. Additional work included the development of procedures for the EPA to use in evaluation of the effects of land use changes and channel modification in urban areas on channel morphology, water quality and biota diversity. Dr. Raphelt also developed the original sediment transport module for the computer program SAM. He has served as Principal Investigator for the Demonstration and Erosion Control Monitoring program that developed a comprehensive design guidance manual that includes techniques for channel stabilization and environmental enhancement. Dr. Raphelt is the author/co-author of 35 Technical Publications, including conference papers, Journal Publications, and ERDC Technical papers, on such topics as: Multidimensional sediment modeling; effects of in channel structures on stream stability, navigation conditions and erosion control; and the effects of flow diversions on sedimentation regimes and stream stability.

Appendix B – Supporting Bibliographic Literature Relied Upon

<u>Thesis and Dissertations (Hardy - major professor or committee member)</u>

Kenneth Behen: Influence of connectivity and habitat heterogeneity on fishes in the Upper San Marcos River, Texas. 2013. MS Thesis, Department of Biology, Texas State University.

Michele Crawford: An analysis of the effects of suspended sediment and photosynthetically active radiation (PAR) on the vegetative growth of Texas wild rice (*Zizania texana*). PhD dissertation, Department of Biology, Texas State University.

Ovie Agarie: Seasonal and longitudinal Investigation of the impacts of recreational activities on aquatic macroinvertebrates community and habitat structure of the San Marcos River. MS thesis, Department of Biology, Texas State University.

Anji Dodd: Two-dimensional mobile bed hydrodynamic model for the transport of mixed sediments. 2006. Dissertation Department of Civil and Environmental Engineering, Utah State University.

Jacob Bilbo: Seasonal impact of recreation based suspension of turbidity on the macroinvertebrate assemblage of the San Marcos River. 2015. MS Thesis, Department of Biology, Texas State University.

Rachel Byrne: Influence of Recreation on Spatial and Temporal Patterns in Water Quality and Periphyton Growth and their Effect on Texas wild-rice (*Zizania texana*). MS Thesis University of Houston – Clear Lake.

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