# PREDICTING CATTAIL RESPONSES TO RE-WATERING OF A TRAVERTINE STREAM: DECOMMISSIONING THE FOSSIL SPRINGS DAM

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## ABSTRACT

## PREDICTING CATTAIL RESPONSES TO RE-WATERING OF A TRAVERTINE STREAM: DECOMMISSIONING THE FOSSIL SPRINGS DAM

Charles E. Jones Jr.

In 1916, the Fossil Springs hydroelectric dam was built near Strawberry, Arizona diverting nearly 100% of the flows from Fossil Creek leaving the stream ecologically degraded. In an effort to restore the creek, a coalition of environmental organizations developed an agreement with Arizona Public Service to decommission the dam. This analysis evaluates the decommissioning alternatives and advocates a restoration target of reinstating key ecosystem patterns and processes. Partially removing the dam and returning full flows to the stream channel will help achieve that target, but two areas of concern are the proliferation of exotic fish and vegetation and post-restoration recreational impacts. A management plan should be developed prior to the initiation of restoration activities to protect against these impacts.

Characteristics of *Typha* patches were examined to determine how *Typha* influences its surroundings through habitat modification. Also, habitat requirements of *Typha* (i.e. flow rate, water depth, sediment depth and canopy cover) were assessed and compared to areas without *Typha*. These measurements were used to determine habitat conditions favorable for *Typha*. I determined that *Typha* slow the water velocity and accumulate sediment within its patch. I also found *Typha* to prefer low canopy cover (0-20%), low water velocity (< 0.107 m/s) and water depths in the middle of its tolerances (40-80 cm). This research resulted in the creation of a relative habitat suitability scale for *Typha* that was used to model *Typha* habitat.

Finally, this research used currently available software and data to create predictive spatial models of *Typha* habitat in Fossil Creek under present and future hydrologic conditions resulting from decommissioning the Fossil Springs dam. The total area of suitable *Typha* habitat was modeled to be 21% less following the removal of the dam. My models illustrate gross changes may occur when dams are decommissioned and natural channel processes are restored to an ecosystem. The decommissioning process should be intensely studied so that the ecological impacts of removing dams are not performed under similar levels of scientific ignorance with which they were installed.

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## DEDICATION

For Cody, Katie, Aurora, Arielle,

Alyssa, Kylie, Alex and

any other children that are

added to our family

Find your path and follow it to its end,

but be sure to have a good time along the way.

And for Jack

whom has already lived that life.

# PREFACE

This thesis was written in the journal format with three chapters that appear in a format appropriate for the journal to which each will be submitted. Chapter two, titled “Designing restoration targets for Fossil Creek, Arizona” provides background information about Fossil Creek that was the basis for defining a restoration target and the recommendations for achieving that target. Chapter three, titled “Determination of habitat characteristics of cattails in a travertine creek” is a manuscript chapter which will be submitted to Aquatic Botany. Chapter four, titled “Creating a predictive model of cattail habitat in a travertine creek” is also a manuscript chapter that will be submitted to Ecological Modelling. There may be some redundancy between chapters, but I have attempted to keep this redundancy to a minimum.

# CHAPTER ONE

## INTRODUCTION

An estimated 75,000 dams have been constructed in rivers and streams throughout the United States (American Rivers 2003). Changes in economic, environmental and aesthetic values have stimulated efforts to remove approximately 460 of these dams (American Rivers 2003). Successful restoration of pre-dam hydrology and biota to the streams and rivers following dam removal depends upon a solid understanding of the patterns and processes that characterize and structure these systems. My thesis research is designed to provide information that will facilitate the restoration of Fossil Creek following the removal of the Fossil Springs dam.

Fossil Creek is a perennial creek on the boundary of the Tonto and Coconino National Forests northwest of Strawberry, Arizona. Groundwater released from Fossil Springs is supersaturated with calcium carbonate ($CaCO_3$), because it flows through a large limestone geologic formation. When supersaturated groundwater equilibrates with the atmosphere, $CaCO_3$ precipitates as arc-shaped travertine dams.

In the early 1900's, most of the perennial flow from Fossil Springs was diverted by installing two dams to produce hydropower for mining operations in the Verde Valley. In 1916, the Fossil Springs dam was constructed 250 meters downstream from the springs and began diverting nearly all of the water (1218 L/s) flow provided by Fossil Springs. Consequently, since 1916, much of the streambed has been nearly dry except for approximately 2.8 L/s of water that leaks from the Fossil Springs dam.

The hydroelectric plants located at Irving and Childs generate a combined 5.6 megawatts per year which is less than 0.1% of Arizona Public Service's (APS) total annual power production (Force, 2002). In 1994, Arizona Public Service (APS) applied to the Federal Energy Regulatory Commission (FERC) to renew their power generation license and continue water diversion from Fossil Creek. As part of the re-licensing process, APS was required to submit an environmental assessment to FERC. Upon review of this document, a coalition of conservation and environmental organizations took an active interest in the re-licensing process and negotiated an agreement with APS to decommission Fossil Springs dam and restore full flows to Fossil Creek by December 31, 2004 (APS, 1992).

Reconstructing riparian ecosystems following dam removal requires stating a *restoration target* and an understanding of the physical, chemical and biological processes that create and maintain the system. Successful ecological restoration requires a solid plan for reinstating the desired structure and function of an ecosystem through managing key ecosystem patterns and processes. Restoration and management plans are generated thorough scientific, economic and social analyses and a balanced decision-making process. The goal of Chapter two is to review and evaluate the scientific and social analyses needed to create a restoration plan for Fossil Creek following the decommissioning of the Fossil Springs dam at the end of 2004.

Cattails, *Typha* sp*.,* are the dominant aquatic macrophyte in Fossil Creek and provide habitat and food for algae, invertebrates, amphibians, reptiles, fish and birds (Fox, 1992; Martin et al., 1982; Payne, 1992; Soszka, 1975). In chapter three, the factors determining habitat suitability of *T. domingensis* were examined in Fossil Creek. Light intensity, sediment depth, water depth and flow rate were measured and analyzed to asses whether they correlated with the presence of *Typha* within Fossil Creek.

The anticipated re-watering of Fossil Creek will alter the hydrologic regime and thus, habitats available for *Typha*, which is the dominant macrophyte in Fossil Creek. In Chapter four, I use the habitat parameters identified in Chapter two to create spatial models of suitable *Typha* habitat in Fossil Creek under present and future hydrologic conditions resulting from decommissioning the Fossil Springs dam.

Countless management decisions have been made during the decommissioning of over 450 dams in the United States during the last 60 years (Hart et al., 2002). Whether to ramp the water flow over time, full or partial removal, how much sediment should be removed from the reservoir, whether to mitigate downstream impacts of the dam removal, etc. Unfortunately, most were made with inadequate levels of scientific information; similar to that of the dam building era (Babbitt, 2002). Creating and testing ecological models will force us to face that scientific ignorance (Poff and Hart, 2002). Fossil Creek provides a perfect opportunity to test the predictive ability of spatial models. The ecological communities will respond to the re-watering of the channel and the purpose of this study is to try to predict the response of macrophytes using currently available hydrologic models, satellite and aerial imagery, digital elevation models and GIS tools.

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## CHAPTER TWO

## DESIGNING RESTORATION TARGETS FOR FOSSIL CREEK, ARIZONA

Charles E. Jones Jr.

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**Abstract**

In 1916, the Fossil Springs hydroelectric dam was built near Strawberry, Arizona diverting nearly 100% of the flows from Fossil Creek leaving the stream channel nearly dry and ecologically degraded. In an effort to restore the creek, a coalition of environmental organizations developed an agreement with Arizona Public Service and the United States Forest Service to decommission the dam. This analysis evaluates the decommissioning alternatives and advocates a restoration target of reinstating key ecosystem patterns and processes. Partially removing the dam and returning full flows to the stream channel will help achieve that target, but two areas of concern are the proliferation of exotic fish and vegetation into the restored stream channel and post-restoration recreational impacts. A management plan should be developed prior to the initiation of restoration activities to protect against these impacts.

*Keywords*: Dam; Fossil Creek; Restoration

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### 1. Purpose / goals

An estimated 75,000 dams have been constructed in rivers and streams throughout the United States, mostly in the last 100 years (Shuman, 1995). Changing economic, environmental, and aesthetic values have stimulated efforts to remove approximately 460 dams and restore the original hydrology and biota to the systems (American Rivers 2003). Reconstructing riparian ecosystems following dam removal should utilize restoration targets and an understanding of the physical, chemical and biological processes that create and maintain the system. These goals are challenging when there is little information about the biological communities and ecological processes that existed before dam construction. Because some physical and ecological changes are irreversible, it may be impossible to return the ecosystem to pre-dam conditions. For example, non-native species have entered the system altering the ecological environment for the native communities that are to be restored. Successful ecological restoration requires a plan for reinstating the desired structure and function of an ecosystem through managing key ecosystem patterns and processes for a specific stream. Restoration and management plans are generated from thorough scientific, economic and social analyses and a balanced decision-making process.

The goal of this paper is to review and evaluate some of the scientific and social analyses needed for a restoration plan for Fossil Creek following the decommissioning of the Fossil Springs dam at the end of 2004.

## 2. Study site

Fossil Creek is a perennial creek on the boundary of the Tonto National Forest and the Coconino National Forest northwest of Strawberry, Arizona (Fig. 2-1). This stream flows at an average rate of 1218 L/s for 22.4 km from a system of springs (Fossil Springs) to its confluence with the Verde River (Malusa, 1997). Fossil Creek drains a 346 km$^2$ watershed.

## 3. Historical hydrological conditions

Groundwater released from Fossil Springs is supersaturated with calcium carbonate ($CaCO_3$), because it flows through a large limestone geologic formation. When supersaturated groundwater equilibrates with the atmosphere, $CaCO_3$ precipitates as arc-shaped travertine dams. In 1891, Lummis described Fossil Springs as being “so impregnated with mineral that they are constantly building great round basins for themselves, and for a long distance flow down over bowl after bowl.” This process created a stunning system of pools, riffles and waterfalls in a unique riparian area nestled among Arizona desert. Above each dam lay the clear blue pools that characterize travertine-forming waters. As water cascaded from one pool into the next, it became oxygenated and ideal habitat for fish and other aquatic organisms. Thus, Fossil Creek was once an ideal “natural fish hatchery” that supported diverse communities of native fish and other fauna (Mockler, 1999). The pools and travertine dams only occurred in the upper reaches of Fossil Creek because within 6.4 km of the springs travertine deposition ceased (Malusa, 1997).

## 4. Dams, diversions and electricity

In the early 1900’s, the perennial flow from Fossil Springs was diverted by installing two dams to produce hydropower for mining operations in the Verde Valley. In 1909, the Fossil Creek diversion dam at Irving was completed and began diverting water from Fossil Creek to the Childs power plant (Fig. 2-1). In 1916, the Fossil Springs dam was constructed (Fig. 2-2) 250 meters downstream from the springs and began the full diversion of the 1218 L/s flow provided by Fossil Springs. The carbonate rich water is now diverted through a flume to the hydroelectric power plant at Irving, where approximately 5.6 L/s of water is released back to the stream channel. The remaining 1212.4 L/s is rerouted and transported to the Childs power plant (Malusa, 1997). Consequently, since 1916, much of the streambed has been nearly dry except for approximately 2.8 L/s of water that leaks from the Fossil Springs dam and runoff from storm flows.

The dam created an artificial pool that has raised the local water table and created a riparian area immediately upstream of the Fossil Springs Dam. This change can be observed by comparing present day and post- dam photos (Figs. 2-3 and 2-4) presented by Monroe (2002). In the 1980's, this unnatural riparian area was given special status and is now referred to as the Fossil Springs Botanical Area on the Coconino National Forest and the Fossil Springs Natural Area on the Tonto National Forest. The pool was identified in a USFS report (2000) as potential habitat for numerous critical species, including the southwestern willow flycatcher (*Empidonax traillii*), Bald eagle (*Haleaeetus leucocephalus*), Yuma clapper rail (*Rallus longirostris yumnensis*), Mexican spotted owl (*Strix occidentalis ludica*) and Chiracahua leopard frog (*Rana chiricahuensis*).

The hydroelectric plants located at Irving and Childs generate a combined 5.6 megawatts per year which is less than 0.1% of Arizona Public Service's (APS) total annual power production (Force, 2002). In 1994, Arizona Public Service (APS) applied to the Federal Energy Regulatory Commission (FERC) to renew their power generation license and continue water diversion from Fossil Creek. As part of the re-licensing process, APS was required to submit an environmental assessment to FERC. Upon review of this document, many questions were raised regarding the unique qualities of Fossil Creek. A coalition of the United States Forest Service, conservation groups and environmental organizations took an active interest in the re-licensing process and eventually negotiated an agreement with APS to decommission Fossil Springs dam and restore full flows to Fossil Creek by December 31, 2004 (APS, 1992). Furthermore, APS has agreed to remove the top six-feet of the dam including the intake structure, the entire aboveground flume system, and to restore the maintenance road to a hiking trail, by the year 2009.

## 5. Dam removal alternatives

Although APS has agreed to remove the top six feet of the Fossil Springs dam, the USFS would prefer that the entire structure be removed for liability reasons. Monroe (2002) and Schlinger, et al. (2003) both analyzed the potential effects of three dam removal options, “no action,” “partial removal” and “complete removal” alternatives. Monroe looked at how the local water table would change, thus altering the riparian plant community and the head-cutting of the stream banks. Monroe also examined how the accumulated reservoir sediments would respond to each option and made predictions regarding how the channel morphology would respond upstream of the existing dam. Schlinger, et al. (2003) analyzed the hydraulics and sediment transport associated with various hydrologic conditions for each dam removal scenario.

### *5.1. No Action*

Monroe determined that under the “no action” alternative, restored flows would increase the base water level of the existing reservoir by 0.76 m and travertine deposits would soon cover the dam.  The existing riparian area that lies upstream of the dam would remain intact (although this riparian area was not present in its current form prior to the construction of the dam).  Retention of the dam will provide a "proven fish barrier" and protect the native fish populations from non-native fish invasion.  Monroe concluded that "no action" is the least expensive and lowest impact restoration option.

### *5.2. Partial Removal*

Monroe (2002) predicts that the "partial removal" option, lowering the dam by six feet, will promote destabilization of reservoir sediment and unpredictable channel migration.  Erosion will continue throughout the Fossil Springs Botanical Area upstream of the dam causing the eventual loss of this dam-derived riparian ecosystem.  The deep pool upstream of the dam will be altered with the loss of the cobble delta that currently maintains its depth.  Gradual removal of the existing reservoir sediment will proceed naturally with moderate flooding intensities, but it may not occur by the restoration deadline of December 2009 stated in the decommissioning agreement because of decreased precipitation associated with climatic variability.  Monroe concluded that the effects of the dam as a fish barrier will be maintained with the partial removal option.  Schlinger et al. (2003) predicted that the partial removal option would maximize the stability of the sediment wedge behind the dam and minimize sediment transport.

### *5.3. Complete removal*

The "complete removal" option is predicted to cause maximum erosional head-cutting that will continue approximately 600 feet upstream of the present dam location (Monroe, 2002). The pool habitats are predicted to revert to channel, and the Fossil Springs Botanical Area will be lost. Moderate flood events with a five-year recurrence interval are expected to be sufficient to move the majority of the accumulated reservoir sediments. These sediments will provide substrate for riparian and aquatic ecosystems as the Fossil Creek ecosystems changes from a pool-riffle structure to a travertine dominated pool-drop structure. Monroe (2002) states that the proven fish barrier will be lost, but predicts that the existing bedrock channel formation will likely maintain sufficient flow velocities to prevent non-native fish from swimming upstream. Complete removal of the dam will result in the restoration of natural channel processes and ecosystems to those that most closely mimic a "pre-dam" Fossil Creek (Monroe, 2002).

Schlinger et al. (2003) predicts that with complete removal, the phreatic surface of the upstream perched aquifer will drop 22 ft to the existing bedrock surface and the pre-dam site topography will be restored. Based on hydrologic and sediment transport models, Schlinger et al. (2003) predict a 100 yr – 12 hour flood event has the potential to create a uniform bed profile gradient which could provide non-native fish a means of migrating upstream of the existing dam location.

**6. Potential outcomes of restoration on physical, chemical and biological characteristics**

No environmental assessments were completed prior to the construction of the Fossil Creek dams and water diversion. Therefore, there is no data to indicate reference conditions and guide ecological restoration efforts. However, several studies have been undertaken at Fossil Creek since the dams' construction that provide useful insights into physical, chemical and biological responses to various restoration scenarios.

*6.1. Geochemistry and geomorphology*

Malusa (1997) found that during a period when full flows were temporarily restored to Fossil Creek, $CaCO_3$ precipitation was 11,952 kg/day throughout entire stream channel. However, when flows were returned to the typical seepage flows (2.8 L/s), the $CaCO_3$ precipitation rate was reduced to only 46 kg/day. Thus, diversion of water from Fossil Creek significantly reduced travertine deposition and continues to alter the natural geomorphology of the channel. Nearly a century of reduced travertine deposition has generated a channel that lacks the complex pool/riffle morphology that once characterized the creek (Santos, 1901). This suggests that travertine deposition will commence following re-watering of the stream channel. It is estimated that increased precipitation rates following re-watering will allow travertine dams and characteristic pools and waterfalls to rebuild relatively quickly, possibly within 10 years (Mockler, 1999). The result will be a channel with the complex geomorphology that was historically characteristic of Fossil Creek.

A natural return of the complex channel morphology may allow for increased sediment deposition in the travertine pools providing substrate for the establishment of riparian and aquatic vegetation, which provide important habitat for birds, fish and macroinvertebrates (Fox, 1992; Payne, 1992; Soszka, 1975). The complex morphology will also provide diverse habitats throughout the watershed and support a wider variety of organisms than streams with simpler channel morphology.

The return of full flows may not be required to restore geomorphic complexity to Fossil Creek. Partial flows could possibly provide similar ecosystem services as full flows. The amount of $CaCO_3$ precipitation and travertine dam formation will be proportional to the quantity of water to be returned to the stream channel. Return of full flows would be ideal to restore natural processes, but Sam Steiger (former mayor of Prescott, Arizona), James Doolittle (Flagstaff consultant), and Dan Israel (Gila County Consultant) have argued against the restoration of flows and the return of partial flows would represent a compromise between the viewpoints (Jones and Phillips, 2001).

### *6.2. Hydrology*

Flash floods are common in low-order streams in the Southwestern United States, and Fossil Creek is no exception. Historical floods in Fossil Creek frequently destroyed or displaced the large travertine deposits, but new dams and pools were reestablished relatively quickly. Malusa (1997) found that some dams grew approximately 1.0 $m^3$ in volume after 43 days under the full flows provided by Fossil Springs. Fossil Creek flood frequency estimates from Monroe (2002) and Schlinger et al. (2003) were converted to graphical form (Fig. 2-5), and used to predict probable flood intervals for different magnitude flood events.

### *6.3. General biology*

Dr. Jane Marks, Northern Arizona University, is currently coordinating efforts to obtain biological profiles of Fossil Creek. This research will provide baseline data of the biology of Fossil Creek prior to the removal of the dam and allow researchers to monitor biological changes throughout the restoration process.

*6.4. Fish*

Native and non-native fish species are present in the lower reaches of Fossil Creek. Populations of non-native fish continue to expand between the Verde confluence and the Fossil Springs dam (Marks et al., 2002; Sponholtz, 2001a; Sponholtz, 2001b). These exotic fish are generally smallmouth bass (*Micropterus dolomieui*) and green sunfish (*Lepomis cyanellus*), but also include flathead catfish (*Pylodictus olivaris)* and yellow bullhead (*Ameiurus natalis)*. Non-native fishes are not found upstream from the dam. Healthy populations of native fish persist upstream of the dam, including: headwater chub *(Giro nigr*a), desert sucker *(Catostomus clarkii*), Sonoran sucker *(Catostomus insigni*s), Longfin dace *(Agosia chrysogaster)* and speckled dace (*Rhinichthys osculus*) (Marks et al., 2002).

Sponholtz (2001b) investigated the composition of fish communities in travertine and bedrock pools. She found that bedrock pools without non-native predatory fishes contained significantly more native juvenile fish than travertine pools. Furthermore, native fish populations are negatively associated with cover in bedrock pools and positively associated with canopy cover in travertine pools.

Chemical renovation, using biotoxins to kill gilled organisms, has been proposed by the U.S. Fish & Wildlife and the Bureau of Reclamation to remove non-native fishes from the ecosystem and maintain Fossil Creek as a native fishery. Without chemical renovation of the non-native fish populations, the existing populations shall persist from the site of the Fossil Springs dam to the confluence with the Verde River. Sponholtz (2001a) suggests, “If management does not intercede and chemically renovate to remove the non-native fishes and construct downstream barriers to fish movement, the outlook for the natives is grim.” Marks et al. (2002) also predicted that chemical renovation will best allow for the restoration of the native fish communities.

Another management alternative suggested by Sponholtz entails promoting Fossil Creek as a roundtail and smallmouth fishery and remove all bag limits in the hopes that sport-fishing take would mitigate the impact of invasive smallmouth predation on endangered indigenous fish (Sponholtz, 2001a). The management of flows to discourage non-native fecundity is an alternative that deserves consideration, but would require further study. However, this option may not be feasible if all water control structures are removed.

### *6.5. Macroinvertebrates*

“Chemical renovation” would eliminate the macroinvertebrate food base of fish unless the treatment is timed to take advantage of the natural restocking of macroinvertebrate eggs. This could be accomplished by renovating the stream with biotoxins just prior to the natural restocking events. Native fish could be restocked from the pools above the dam, but it may be desirable to restock the channel.

Marks et al. (2002) found two (out of 119) macroinvertebrate species of special concern (i.e. threatened, endangered, rare or sensitive) in the Fossil

Creek watershed which could be adversely affected by the use of biotoxins. The highest diversity of macroinvertebrate species were found in travertine depositing sections of the stream. Marks et al. (2002) also found that crayfish represent a potentially severe threat to a re-watered Fossil Creek. The authors also state that the macroinvertebrate community may be adversely affected by increased sediment transport associated with the dam removal, but that these impacts will be relatively short lived (less than 10 years). Overall, dam removal will result in an increase in the macroinvertebrate food base and the standing crop of algae (Marks et al., 2002).

### *6.6. Recreational impacts*

Restoration of Fossil Creek will generate a unique and lush ecosystem. Without proper planning, recreational impacts to this system could be tremendous. Some ideas to mitigate the impacts of recreation have been discussed, but no plans currently exist to accommodate the anticipated increase in recreational traffic. There are many methods to minimize recreation impacts, including developing park infrastructure through trails, picnic areas, restroom facilities and camping sites. These areas would offer protection by sacrificing non-sensitive areas along the stream corridor. Sponholtz (2001a) stated that the USFS has asked APS to leave the structures near the Irving facility. These could be used as cabins for visitors or administrative buildings for the USFS. Cabins might provide some income for USFS to maintain the area. Some of the conservation groups are strongly against this option because they want all human structures removed from the area.

## 7. Design for future research and monitoring

I support conducting research and monitoring throughout every aspect of the restoration. Intensive studies should be conducted before the dam is removed and continued throughout the restoration process so that changes can be monitored over time. Re-watering Fossil Creek provides a unique opportunity to study physical, chemical and biological responses to stream restoration that are relevant to the restoration of other arid-land riparian areas.

A survey of the stream channel at current base flows should be completed prior to dam removal. This will allow for the continuously changing geomorphology of Fossil Creek to be monitored, facilitating further geochemical research in the travertine waters of Fossil Creek. Malusa (1997) modeled numerous aspects of the Fossil Creek travertine system, but he did not provide estimates of the changing rates of travertine aggradation throughout Fossil Creek. These estimates would be useful in creating models of the morphologic changes in the channel overtime, which would allow for accurate estimates of water depths and flow rates in the stream. These estimates could be used to predict the suitable habitat for species of concern throughout the watershed.

A survey of the water channel would provide a high-resolution digital elevation model (DEM) for the area. DEMs are a digital model of the land's topography. These high resolution DEMs offer an accurate representation of the landscape on a fine scale. Currently, the best DEMs offered by the USGS have a 10 m pixel resolution. This means that each area that measures 10 m x 10 m is provided with a single elevation. This resolution is good for many applications, but considering the travertine deposition of Fossil Creek and the highly variable channel morphology, it is not adequate for habitat modeling in Fossil Creek. Under the current flow regime, most cross sections of the stream are less than 5 m wide, which is the minimum required to indicate the presence of water under a DEM with a 10 m pixel resolution, I recommend obtaining DEMs with 1 m pixel resolutions to adequately model habitat in Fossil Creek.

Recreational traffic to Fossil Creek is predicted to increase following the restoration of flows to the channel. The final area of research that should be pursued is how changes in recreational traffic will impact the geomorphic and biological components of Fossil Creek. Are certain areas and species more sensitive than others? If so, how might managers ameliorate impacts to these areas? These issues should be addressed to minimize recreational impacts to the Fossil Creek ecosystem after the restoration process begins.

**8. Restoration target**

A restoration goal for Fossil Creek has not been stated by the USFS. Should the restoration target be to 1) return the natural ecosystem patterns and processes, 2) to return to some predetermined historical condition, or 3) to maintain the existing Fossil Springs Botanical Area? Each of these goals may entail different restoration strategies. I propose that the restoration goal should be to reinstate Fossil Creek's natural structure and function by reinstating key ecosystem patterns and processes. Restoring flows to Fossil Creek will return travertine deposition to the channel. The associated changes in geomorphology are a major ecosystem pattern in Fossil Creek, thus restoring Fossil Creek to a dynamic travertine based system will have ecosystem level effects.

## 9. Restoration recommendations

The following recommendations should help reinstate ecosystem patterns and processes in Fossil Creek.

### *9.1. Hydrology and geomorphology*

From an ecological perspective, the return of the full 1218 L/s to the stream channel will allow the characteristic travertine dams to develop and offer a structurally complex channel. This complex channel will increase sedimentation rates and encourage natural re-colonization by riparian vegetation, thus providing a more diverse habitat for fish, macroinvertebrates and birds.

### *9.2. Dam removal*

I recommend partial dam removal. Monroe (2002) states that the water table will be lowered similarly by both partial- and complete- removal options, thus having similar effects on the associated riparian vegetation and the channel structure. USFS biologists determined that partial removal would have less impact on species of special status than complete removal because there would be less drastic habitat changes associated with partial removal (USFS, 2000). Therefore, partial removal would best return natural channel processes to Fossil Creek and would return the ecosystem associated with the reservoir to an ecosystem that more closely resembles that present prior to the construction of the dam. The partially removed dam would be covered in travertine in a relatively short period and would create an aesthetically pleasing channel feature. It would continue to serve as a fish barrier and discourage the establishment of non-native fish species upstream of the dam.

### *9.3. Recreational impacts*

Finally, measures must be taken to ameliorate recreational impacts by establishing designated parking areas, trails, picnic areas, restroom facilities and camping sites. By offering these facilities, the USFS will be able to direct the increased recreational impacts to particular areas, lessening the impact to more sensitive areas.

## 10. Acknowledgments

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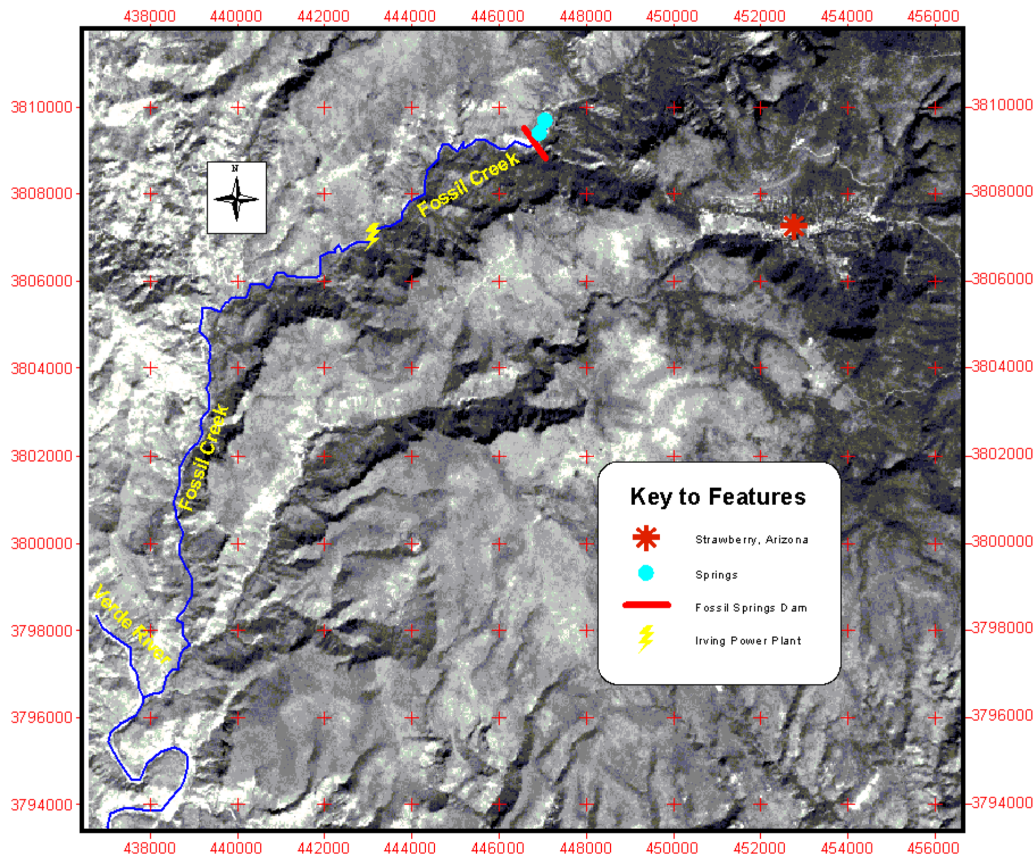


Fig. 2-1. Fossil Creek and surrounding area. Map created by Chas Jones on 5/27/2003 using Arcview 3.2. Projection: UTM NAD 83, Zone 12N.

Fig. 2-2. Construction of the Fossil Springs dam started in 1916. Photo courtesy of Arizona Public Service.

Fig. 2-3. Fossil Springs damsite prior to dam construction. ((Whitsit, 1915); Courtesy Special Collections, Northern Arizona University).

Fig. 2-4. Fossil Springs damsite in 1999 (Image from Monroe (2002)).

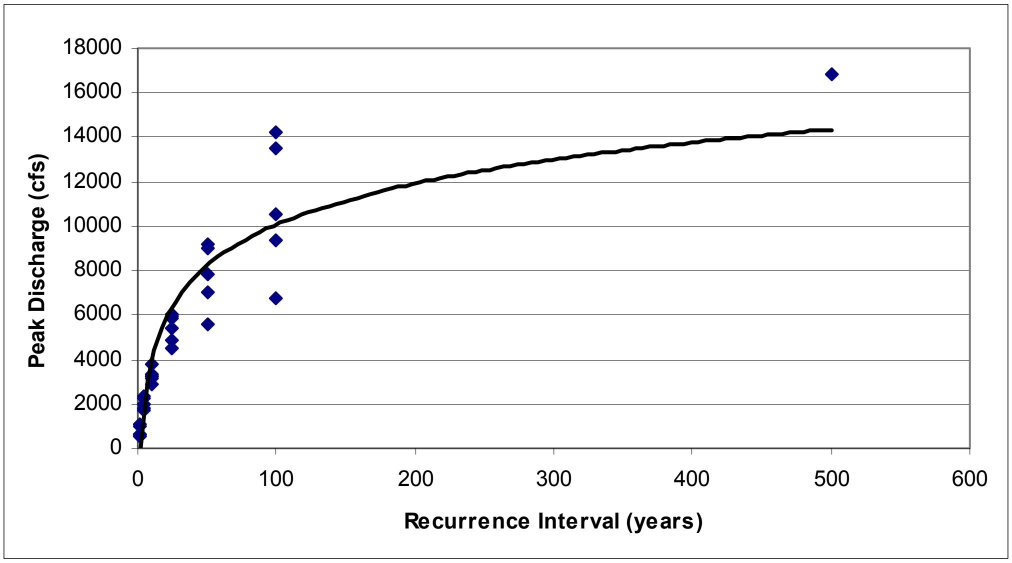


Fig. 2-5. Flood recurrence interval for Fossil Creek (modified from data presented by Monroe (2002) and Schlinger et al. (2003)). Base flow is approximately 1218 L/s.

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# CHAPTER THREE

# DETERMINATION OF HABITAT CHARACTERISTICS OF CATTAILS IN A TRAVERTINE CREEK

Charles E. Jones Jr.

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**Abstract**

Characteristics of *Typha domingensis* patches were examined to determine how *T. domingensis* influences its surroundings in a travertine creek. The habitat requirements of *T. domingensis* (i.e. flow rate, water depth, sediment depth and canopy cover) were also assessed and compared to areas without *T. domingensis*. These measurements were used to determine habitat conditions favorable for *T. domingensis*. Results indicate that *T. domingensis* modify its surroundings by slowing the water velocity and accumulating sediment. Also, *T. domingensis* prefers low canopy cover (0-20%), low water velocity (< 0.107 m/s) and water depths in the middle of its tolerances (40-80 cm). This research resulted in the creation of a relative habitat suitability scale for *T. domingensis* that could be used to model *T. domingensis* habitat in Fossil Creek, Arizona.

*Keywords*: Cattail; Ecosystem engineer; Habitat; *Typha*

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## 1. Introduction

*Typha domingensis* (formerly *T. angustata*) is a native, perennial, monocot that has a worldwide distribution, and is common throughout the southern and mid-latitude states of the United States (USDA and NRCS, 2002). *Typha* species are usually found in ponds, lakes, marshes and drainage ditches, but they also occur along the shoreline of creeks or streams where water velocities are low. *Typha* are sometimes considered undesirable and “weedy” (Baker, 1974; Radosevich and Holt, 1984) because they can impede water flow and promote the silt deposition (Fox, 1992; Grace and Harrison, 1986; Young and Blaney, 1942). Cattail patches tend to create dense monospecific stands that reduce the ratio of open water to vegetation, decrease the diversity of vegetation, and reduce habitat value (Brown and Bedford, 1997). *Typha’s* copious seed production and competitive ability contribute to its invasive properties (Roberts, 1984). Expansion of mature cattail stands is indicative of Phosphorus enrichment (Craft and Richardson, 1997; Doren et al., 1997) and altered hydrology (Newman et al., 1996), both of which are negative side-effects of human activities.

Yet, T*ypha* species are also positive components of aquatic ecosystems because they provide food, substrate, and refuge for epiphytic algae, microorganisms, invertebrates, fish, and birds (Claassen, 1918; Fox, 1992; Martin et al., 1982; Payne, 1992; Soszka, 1975). *Typha* provide resources and modify the environment in ways that create habitats for other organisms. Human activities may affect communities and associated ecosystems by creating, destroying or modifying habitat for *Typha domingensis.* It is necessary to better understand the habitat requirements of *T. domingensis* before this species can be effectively managed in streams and rivers.

Many studies have described habitat preferences of *Typha* species in lentic environments; however, it is unclear whether these preferences will be similar in lotic environments. Light requirements, pH, temperature and water depth have been characterized for many *Typha* species in lakes, ponds and marshes (Table 3-1), but little is known about the effects of water velocity on their distribution in streams and rivers. This study examines the habitat characteristics of, and habitat modification by, *T. domingensis* in Fossil Creek in central Arizona, USA. This lotic system is an excellent site to assess the habitat preferences and habitat modification by *T. domingensis* because its flow is perennial and *T. domingensis* is the dominant macrophyte in this system.

Environmental requirements and competitive characteristics abilities of species help predict habitat requirements of aquatic macrophytes (Fox, 1992). Special attention should be given to water velocity because management of stream flow rates can be used to control populations of *Typha.* Organisms both respond to environmental conditions and influence the environment. It is likely that *Typha* patches influence water velocity and sediment depth, and thus once they become established in an area, their impacts on lotic environments can influence the habitat suitability for other organisms.

This research was designed to test three hypotheses by asking six questions.

Hypothesis 1: Habitat suitability for *T. domingensis* is related to canopy cover, flow rate, water depth and sediment depth.

- Do *T. domingensis* patches in Fossil Creek occur in areas with water depths, water velocities, canopy cover and sediment depths that differ from paired areas without *Typha*?
- Are patch size dynamics indicative of habitat suitability? If so, then large patches should increase in area significantly more than small patches.

- Are water depth, water velocity, canopy cover and sediment depth correlated with the patch dynamics of *T. domingensis*?

Hypothesis 2: *Typha domingensis* modify flow rate and sediment depth in streams.

- Does *Typha* reduce water velocity?
- Does *Typha* influence sediment depth?

Hypothesis 3: Emergent macrophytes share habitat preferences.

- Is there a correlation between *T. domingensis* habitat and habitat for *Scirpus* spp., *Equisetum hymale, or Equisetum arvense*?

## 2. Methods

### *2.1. Study site, lab and field measurements*

Fossil Creek is a perennial stream fed by Fossil Springs northwest of Strawberry, Arizona. Fossil Creek's water is supersaturated with calcium carbonate ($CaCO_3$), which precipitates in the form of travertine dams that create a pool – drop stream morphology. Twenty locations without *T. domingensis* were randomly identified within each of twenty 0.3 km sections along a 6 km segment of Fossil Creek and each of these "bare" sites was then paired with its nearest *Typha* patch. During July and August of 2001 and 2002 the surface area of the twenty *T. domingensis* patches was estimated at each site using 30-m measuring tapes. Water depth at each site was also measured using either a meter stick or a 30-m tape. Riparian canopy cover above each of the *T. domingensis* patches and the paired bare areas was measured using a densiometer. Water velocity and sediment depth were measured within *T. domingensis* patches and their paired bare sites and also 10, 50 and 100 cm upstream and downstream of the patches and bare sites. Sediment depth was measured using a meter stick and base flow water velocities were measured using the Global Flow Probe FP

101(Global Water Instrumentation, Inc, Gold River, CA, USA, sensitivity = ± 0.005 m/s) according to the manufacturers instructions. The measurements taken 100 cm upstream of the *T. domingensis* patches were assumed to not be impacted by the patches.

The estimated maximum annual growth rate for a newly established *Typha* seedling is 7.3 $m^2$, therefore, *Typha* patches were separated into two size classes, small (< 7.3 $m^2$) and large (> 7.3 $m^2$) (Yeo, 1964). Patch expansion rates were determined by observing changes in patch size over two summers. Locations with high patch size expansion rates were assumed to have higher habitat than locations where *T. domngensis* patches were stable or declining in size. The presence of Bulrush (*Scirpus* spp.) and Horsetail (*Equisetum* spp.) were noted at each *Typha* patch and each paired bare site to determine whether there were correlations between the habitats of these species and *Typha*. Their presence was noted if it was within visual range of the site.

### *2.2. Statistical analyses*

The paired data (Bare vs. *Typha*) was first analyzed by the Shapiro – Wilk test to test for departures from normality. If the Shapiro – Wilk $p > 0.05$, then the parameter was analyzed with a paired t-test; otherwise, the data was analyzed with a Wilcoxson signed rank test (non-parametric version of a paired t-test). To analyze the data by patch size (large and small), Bartlett's and Shapiro – Wilk tests were used to test for equal variance and extreme departures from normality. If Bartlett's was > 0.05 for a given parameter, the data were analyzed with an independent t-test; otherwise, the Mann – Whitney U test was used (non-parametric version of the independent t-test). *Scirpus* and *Equisetum* presence / absence data was analyzed with a $X^2$ test. The sediment depth and water velocity profile data was analyzed with Bartlett's test and an ANOVA if Bartlett's was > 0.05; otherwise a Kruskal-Wallis (non-parametric version of ANOVA) followed by a post-hoc Tukey-Kramer analysis was used to test for significant differences. All statistical analyses were performed using SAS JMP v. 4.04 (SAS Institute, 2001).

## 3. Results

### *3.1. Patch size dynamics*

In 2001, the average small patch size was 1.53 ± 0.39 $m^2$ and the large patches averaged 68.9 ± 28.8 $m^2$. Between 2001 and 2002, the average surface area of small patches contracted by 49% while large patches expanded 44% (Fig. 3-2A), indicating significantly different rates of expansion ($p = 0.011$). Furthermore, during the study period, 64% of small *T. domingensis* patches decreased in size by at least 66%. No large patches decreased in size to this degree (Fig. 3-2A).

### *3.2. Assessment of habitat parameters*

Seventy percent of all *Typha* stands were found under less than 50% riparian canopy cover (Fig. 3-3). Large *Typha* patches are more common under low canopy cover than high canopy cover (Fig. 3-3). On average, small patches occurred in areas with 35% greater canopy cover than large patches (Fig. 3-2B). Bare sites and *Typha* patches were found under similar canopy coverage (Fig. 3-4A). Ninety-five percent of the water velocity measurements taken 100 cm upstream from *T. domingensis* patches were very low (0.005 m/s to 0.01 m/s), and there was no difference in water velocity measurements between small and large patches (Fig. 3-2C). *Typha* patches occurred in areas with water flowing 96% slower than in their paired bare sites (Fig. 3-4B, $p$ = 0.03; Fig. 3-5A). Water velocity in the paired bare areas ranged from .005 m/s to 5.88 m/s. *Typha* patches occurred in water depths that ranged from 0 to 111 cm. Large patches were most common in deeper water than small patches, 78% of large patches were found in water depths greater than 20 cm (Fig. 3-2D, $p$ = 0.01), but there were no differences between the water depths of bare and *Typha* sites (Fig. 3-4C). Sediment depth 100 cm upstream of *T. domingensis* patches was not significantly deeper than that in paired bare areas (Fig. 3-4D; Fig. 3-5B) and there is no difference in sediment depth 100 cm upstream of small or large patches (Fig. 3-2E).

### *3.3. Habitat modification and coexistence of macrophytes*

*Typha* patches reduced water velocity as it flowed near and into the patch. After leaving the patch, water velocity increased rapidly (Fig. 3-5A). Sediment depth was significantly greater within patches of *T. domingensis* than upstream or down stream of the patches or at the paired bare sites (Fig. 3-5B). *Equisetum* was only present when *Typha* was also present, but it was not present at each *Typha* patch ($X^2$ = 13.8, $p$ = 0.0002). *Scirpus* was also present only when *Typha* was present except in one case, but it was not present at each *Typha* patch ($X^2$ = 13.8, $p$ = 0.0002).

## 4. Discussion

### *4.1. Assessment of habitat suitability*

Patch expansion was assumed to indicate favorable habitat conditions. Yeo (1964) found that a single *T. latifolia* seedling could develop a 7.3 $m^2$ system of rhizomes in a single growing season under favorable conditions. It is known that *T. domingensis* reproduces vegetatively at a faster rate than *T. latifolia* (Grace and Harrison, 1986), so the assumption that small patches are < 7.3 $m^2$ is conservative. In Fossil Creek, small patches usually contained small individuals that were not reproducing clonally, while large patches contained larger individuals that were reproducing clonally. On average, large patches expanded 44% over the period of a year, thus indicating that they were growing in favorable habitat. During the same period, small patches contracted 49% (Fig. 3-2A). Thus, large patches are found in the most suitable habitat conditions.

The results of this study corroborate those found by other researchers in lentic systems (Table 3-1). Numerous authors have found that light intensity is an important environmental requirement for *Typha* spp. (Gopal and Sharma, 1983; Lorenzen et al., 2000; Sharma and Gopal, 1979b). Our research shows low canopy cover (0-20%) is most favorable for *Typha* in Fossil Creek. Because light intensity is directly related to canopy cover (Bellow and Nair, 2003), we conclude that our research also indicates that *Typha* is more common (Fig. 3-3) and growth rates are higher (Fig. 3-2A) under low light (i.e. low canopy cover) in lotic systems.

It is widely recognized that water depth is important in *Typha* establishment (Grace and Wetzel, 1981; Miao et al., 2001; Weisner, 1993). This research found that deeper water is more favorable habitat for *T. domingensis* within its tolerance range, which is typically 0-120 cm (Chambers et al., 1995; Grace, 1989). Other researchers have been able to determine that the tolerance range could be split into 4 distinct categories. Sharma and Gopal (1979b) found that *T. domingensis* did best in water depths at the middle of its tolerance range with mediocre growth responses at the extremes of its tolerances. Our data, suggests three classes, but this could be an artifact of the small sample size of patches within the deep-water zone of its tolerances (80-120 cm). After considering their findings, this habitat suitability scale was split into four categories with the middle depths of 40 – 80 cm representing the most favorable habitat (Table 3-2).

A severe drought occurred during the summers of 2001 and 2002. The 1965 – 2003 hydrograph of West Clear Creek (which is the nearest stream gage to Fossil Creek) shows that peak flows during 2001 and 2002 were substantially less than previous years (Fig 3-1). Consequently, the patch expansion rates of the *T. domingensis* patches in this study may have been greater than in typical years.

### *4.2. Habitat modification*

Sediment depths were not significantly different 100 cm upstream of the bare and *Typha* sites (Fig. 3-5B. These results indicate that *T. domingensis* do not preferentially select areas with greater sediment depths than typical of Fossil Creek, but that *T. domingensis* modifies its environment by slowing the water (Fig. 3-5A) and allowing sediment to settle at its base (Fig. 3-5B). This finding supports those of Grace and Harrison (1986) and Young and Blaney (1942) and indicates that sediment depth is not a determining factor for *T. domingensis* habitat suitability but rather, *Typha* patches trap sediment after they become established.

Most of the field research conducted on *Typha* has been done in stagnant or slow moving water (Grace and Harrison, 1986; Squires and van der Valk, 1992; Weisner, 1993). The hydraulic diversity of streams and rivers offer more complex modeling issues than are typically found in lakes and ponds. To our knowledge, this is the first study to assess flow rate tolerances of a *Typha* species. This research shows that water velocity may be an important determinant of suitable *Typha* habitat in lotic environments. *Typha* was found in significantly slower water than typical of Fossil Creek (Fig. 3-4B). Interestingly, no relationship was found between flow rate and patch size. This indicates that after establishment, still and flowing water represent equally favorable habitat for *Typha*.

### *4.3. Conclusions and implications*

More research is necessary to determine whether water velocity is a determining factor in establishment of *Typha* seedlings. In Fossil Creek, flash floods appear to act as an important control mechanism by physically removing or damaging *T. domingensis* patches. It would be interesting to determine whether this is a common occurrence in streams and rivers that experience flash floods.

This research determined the relative habitat preferences of *Typha* in Fossil Creek. In Fossil Creek, it is evident that *Typha* is sensitive to canopy cover, flow rate and water depth. *Typha* was found to prefer low canopy cover (0-20%), low water velocity (< 0.107 m/s) and middle water depths (40-80 cm). Habitat suitability scales can be used to determine how organisms may respond to changes in their environment and may become very important as ecologists attempt to model changes in the world around us.

Macrophytes provide many important ecological services for invertebrates, fish, mammals, birds and epiphytic algae. It becomes apparent that *Typha* strongly influences its environment by diversifying habitat conditions for other organisms (Jones et al., 1994). These habitat modifications likely have community or even ecosystem level effects.

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Table 3-1
Measured habitat characteristics of *Typha* in various aquatic habitats

| Parameter | Species | Habitat characteristics | Habitat type | Studies |
|---|---|---|---|---|
| Light intensity | *T. domingensis* | Seed germination directly correlated with intensity | Lab | (Gopal and Sharma, 1983) |
| | *T. domingensis* | Seedlings do not survive at less than 2500 lux | Chamber | (Sharma and Gopal, 1979b) |
| | *T. domingensis* | Rhizomes develop at greater than 7500 lux | Chamber | (Sharma and Gopal, 1979b) |
| | *T. domingensis* | Light required for germination | Chamber | (Lorenzen et al., 2000) |
| | *Typha* sp. | Seedlings establishment may be limited by light | | (Grace and Harrison, 1986) |
| Alkalinity | *T. angustifolia* | Tolerates more alkaline water than T. latifolia | | (Crow and Hellquist, 1981) |
| | *T. latifolia* | Tolerates some acidity | | (Smith, 1967) |
| Temperature | *T. angustifolia* | Tolerates down to -13 Celsius | | (Smith, 1967) |
| | *T. angustifolia* | Cold sensitive | | (Grace and Harrison, 1986) |
| | *T. domingensis* | Cold sensitive | Marsh | (Miao et al., 2001) |
| | *T. domingensis* | Diurnal fluctuation increases germination | Chamber | (Lombardi et al., 1997) |
| | *T. domingensis* | Fluctuating temperatures not required for germination | Chamber | (Lorenzen et al., 2000) |
| | *T. latifolia* | Tolerance range is down to -34 Celsius | | (Smith, 1967) |
| Water depth | *T. angustifolia* & *T. domingensis* | Tolerance range is 0 - 120 cm | Lake | (Weisner, 1993) |
| | *T. angustifolia* & *T. latifolia* | Prefers mid-water depths in tolerance range | Pond | (Grace and Wetzel, 1981) |
| | *T. domingensis* | Critically affects seedling survival and growth | Chamber | (Sharma and Gopal, 1979b) |
| | *T. domingensis* | Tolerance range is 0-120 cm | Pond | (Chambers et al., 1995) |
| | *T. domingensis* | Seedling growth best under 10 cm | Bucket | (Sharma and Gopal, 1979a) |
| | *T. domingensis* | Specific needs for seed germination & survival | Marsh | (Miao et al., 2001) |
| | *T. latifolia* | Requirements for successful establishment | | (Grace and Harrison, 1986) |
| | *T. latifolia* | Tolerance range is 15-75 cm | Lake | (Weisner, 1993) |
| | *T. latifolia* | Tolerance range is 15-95 cm | Pond | (Grace, 1989) |
| | *T. latifolia* | Germinates in up to 30 cm water | Pond | (Yeo, 1964) |
| Photoperiod | *T. latifolia* | Optimal growth rates at 12 h / 12 h photoperiod | Chamber | (Lombardi et al., 1997) |
| | *Typha* sp. | Seedling establishment limited by photoperiod | | (Grace and Harrison, 1986) |
| Salinity | *T. angustifolia* | Associated with basic, calcareous or salty soils | | (Smith, 1967) |
| | *T. angustifolia* & *T. latifolia* | T. angustifolia tolerates more halophillic than T. latifolia | | (Crow and Hellquist, 1981) |
| | *T. latifolia* | Tolerates some salinity | | (Hotchkiss and Dozier, 1949) |
| Elevation | *T. angustifolia* | 0-6000 ft | | (Smith, 1967) |
| | *T. latifolia* | 0-7000 ft | | (Grace and Harrison, 1986) |

Table 3-2

Habitat suitability scale for *Typha* habitat preferences

| **Canopy** | | **Flow rate** | | **Water depth** | |
|---|---|---|---|---|---|
| Most suitable | 0 - 20 % | | | Most suitable | 40 - 80 cm |
| More suitable | 21 - 40 % | | | | |
| Suitable | 41 - 60 % | Suitable | < 0.107 m/s | Suitable | 0 - 40 cm, 80 - 120 cm |
| Less suitable | 61 - 80 % | | | | |
| Least suitable | 81 - 100 % | Not suitable | > 0.107 m/s | Not suitable | > 120 cm |

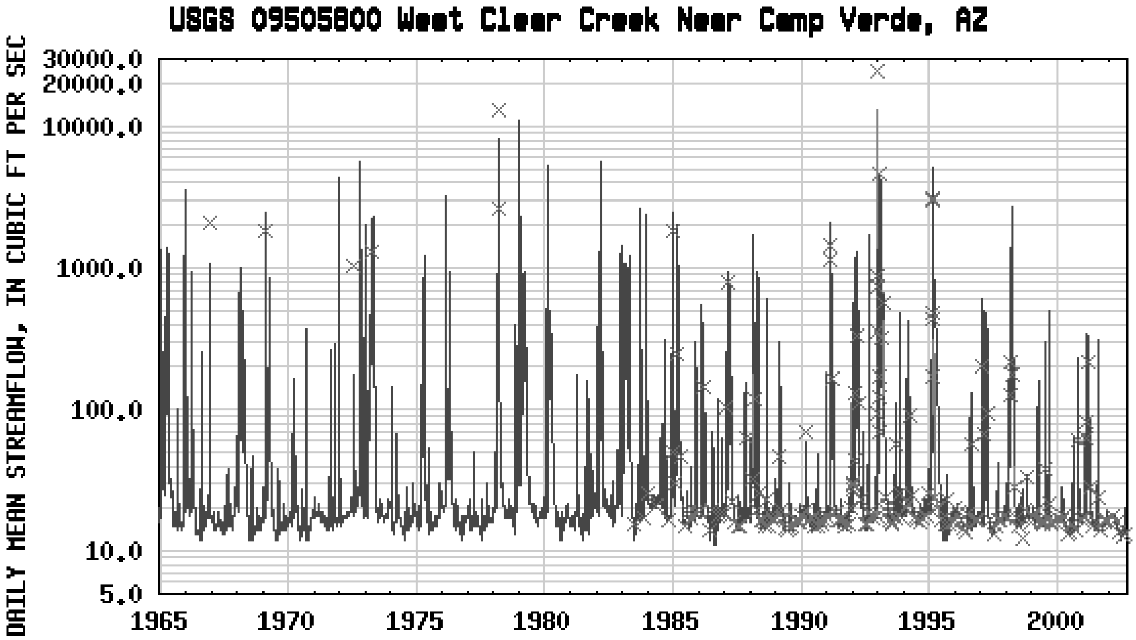


Fig 3-1.Hydrograph of West Clear Creek from 1965 – 2003 shows the severe drought of the 2001-2002 field seasons compared to historical data.

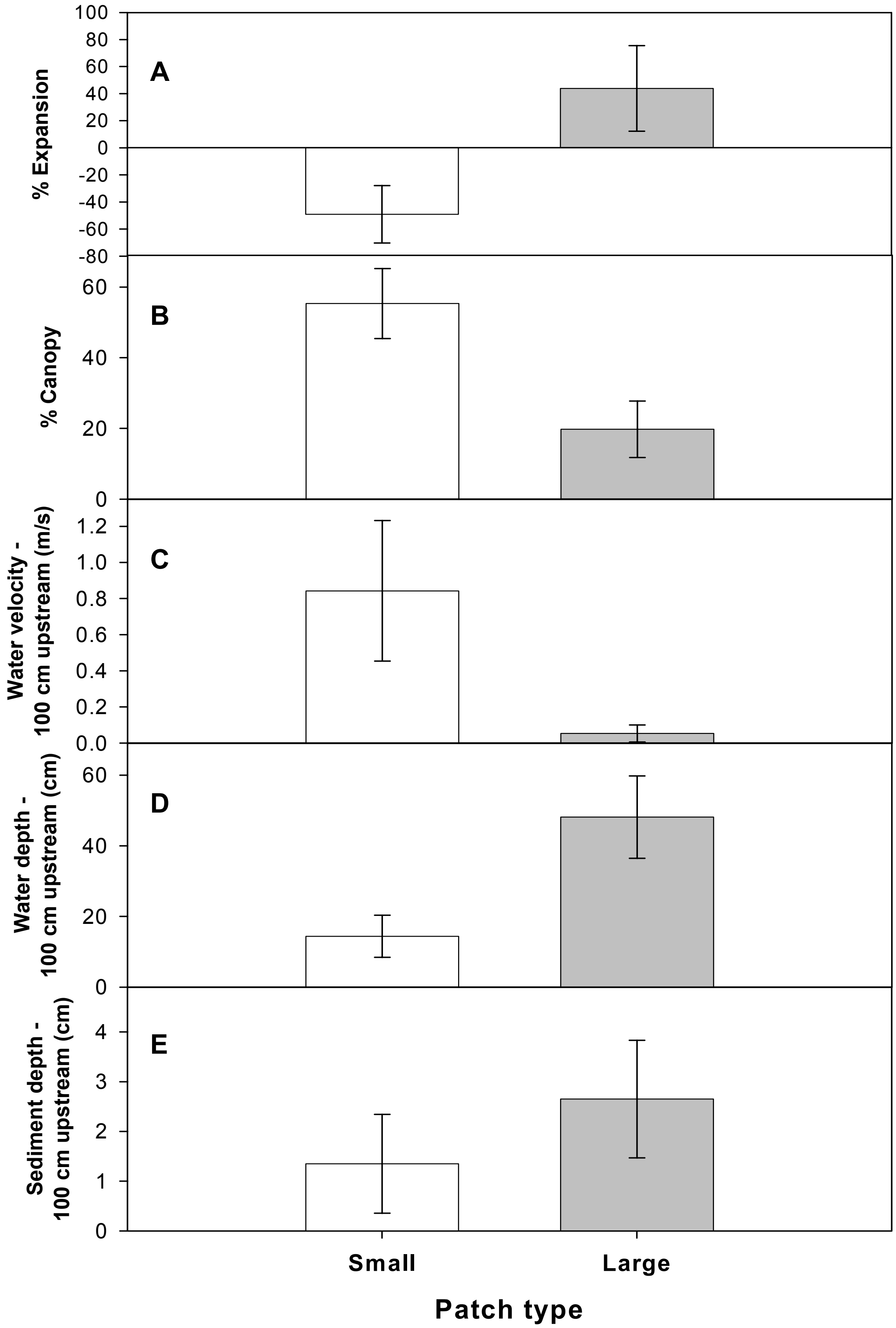


Fig. 3-2. Relationship between *T. domingensis* stand size and patch expansion (A), percent canopy cover (B), water velocity (C), water depth (D) and sediment depth (E) in Fossil Creek. Each, except expansion and canopy, was measured 100 cm upstream of the patch. Mean (S.E.), n = 11 for small patches; n = 9 for large patches.

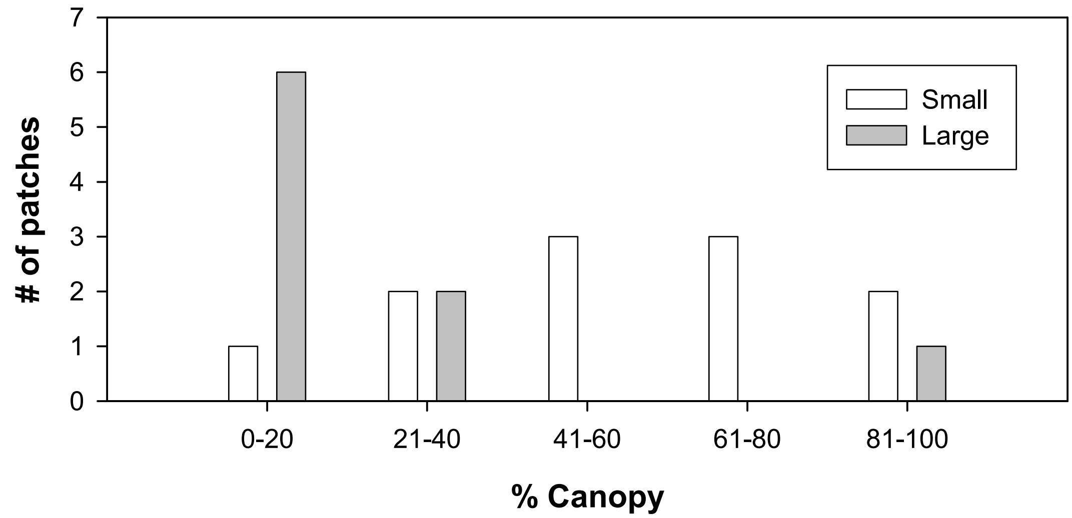


Fig. 3-3. Number of *T. domingensis* patches found under five classes of riparian canopy cover in Fossil Creek (n = 11 for small patches; n = 9 for large patches).

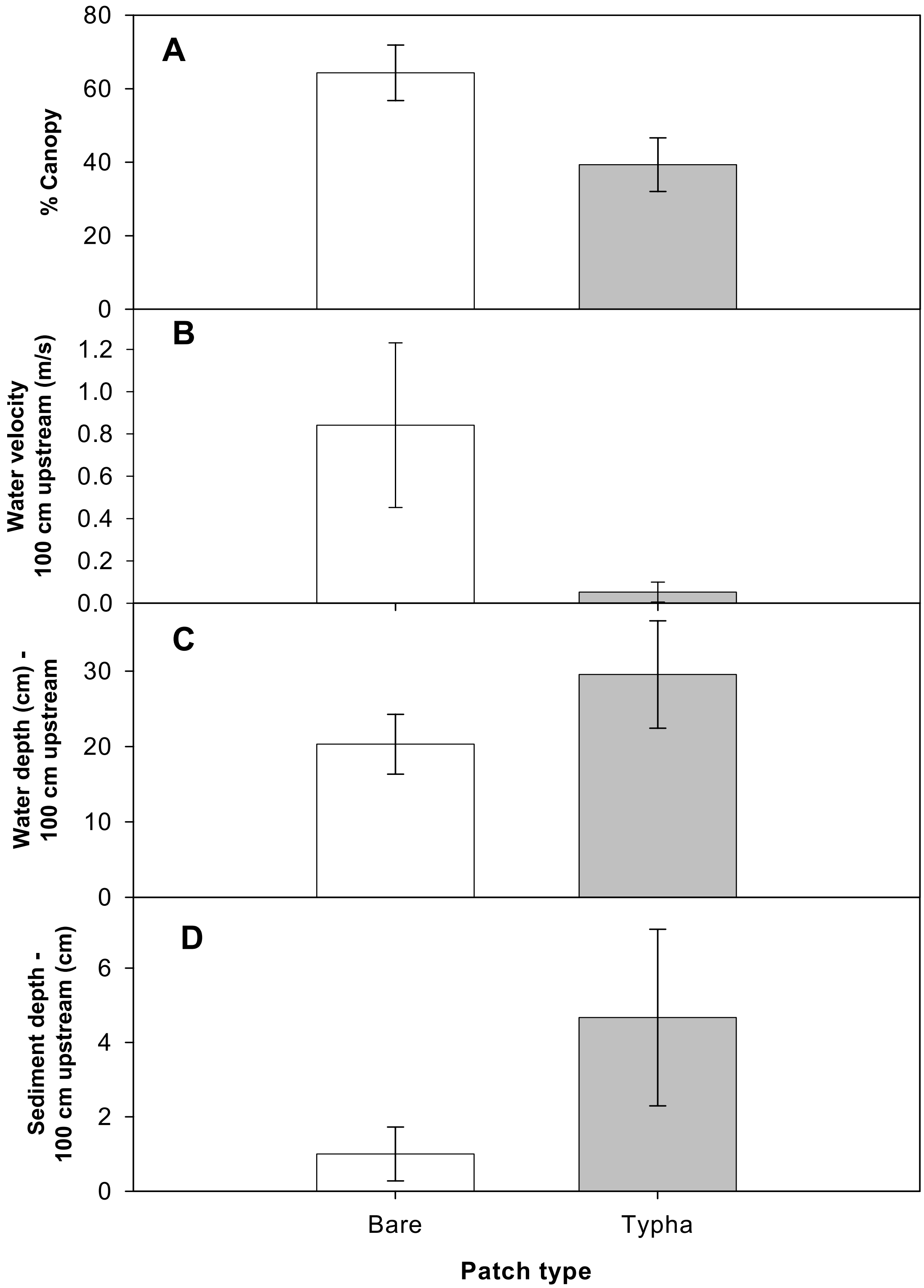


Fig. 3-4. Comparison of % canopy (A), water velocity (B), water depth (C) and sediment depth (D) in *T. domingensis* patches and paired bare sites in Fossil Creek. Each parameter was measured 100 cm upstream of each patch except canopy cover. Mean (S.E.), n = 20.

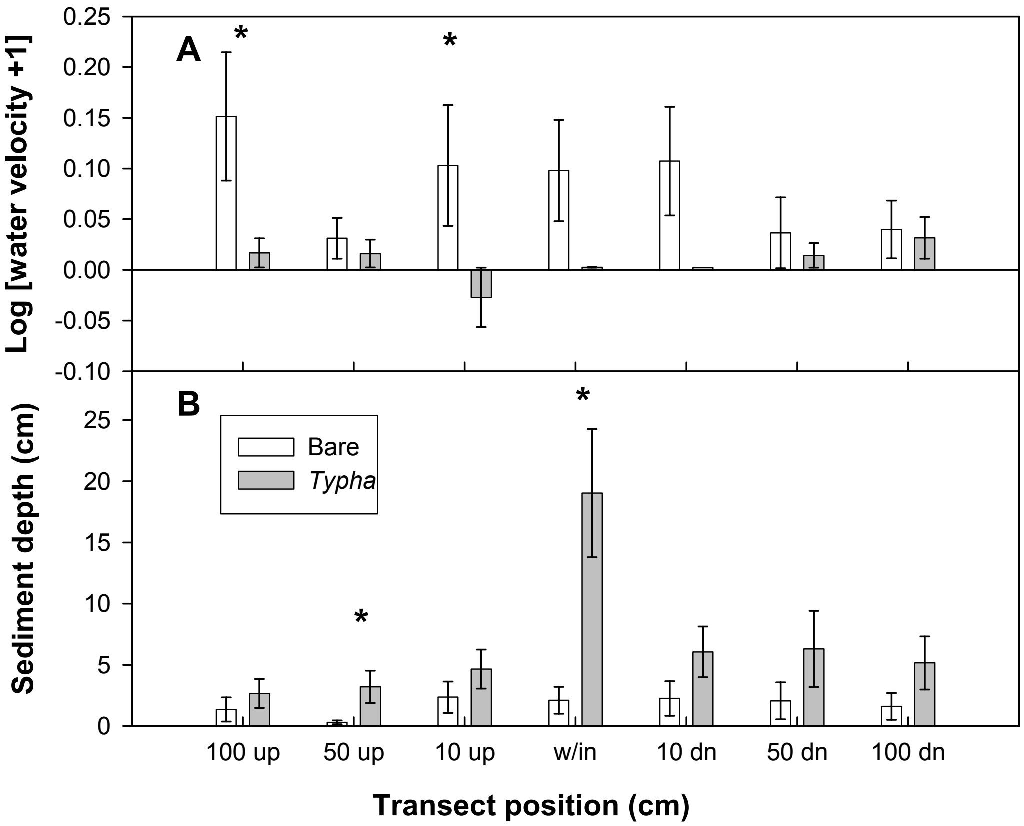


Fig. 3-5. Water velocity (A) and sediment depth (B) measured 100 cm, 50 cm and 10 cm upstream and downstream and within *T. domingensis* patches (shaded bars) and in paired bare sites (open bars) in Fossil Creek. Mean (S.E.). "*" indicates water velocity or sediment depth in bare and *Typha* sites differ significantly, $p < 0.05$.

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## CHAPTER FOUR

## CREATING A PREDICTIVE MODEL OF CATTAIL HABITAT IN A TRAVERTINE CREEK

Charles E. Jones Jr.

### Abstract

The anticipated re-watering of Fossil Creek will alter the hydrologic regime and habitat available for macrophytes. This study uses currently available software, digital elevation models, and satellite and aerial imagery to create predictive spatial models of *Typha* habitat in Fossil Creek under present and future hydrologic conditions resulting from decommissioning the Fossil Springs dam. Re-watering Fossil Creek was modeled to reduce the total area of suitable *Typha* habitat by 21%. My models illustrate gross changes may occur when dams are decommissioned and natural channel processes are restored to an ecosystem. The decommissioning process should be carefully monitored to maximize the knowledge gained about dam removal.

*Keywords*: Cattail; Dam; Habitat; Model; Travertine; *Typha*

### 1. Introduction

#### *1.1. Historical Background*

Fossil Creek is a perennial, spring-fed stream on the boundary of the Tonto and Coconino National Forests northwest of Strawberry, Arizona (Fig. 4-1). Groundwater released from Fossil Springs is supersaturated with calcium carbonate ($CaCO_3$), which precipitates as arc-shaped travertine dams as it equilibrates with the atmosphere. In the early 1900's, the perennial flow from Fossil Springs was diverted at two dams used for hydropower for mining operations in the Verde Valley. The carbonate rich water is now rerouted to hydroelectric power plants at Irving and Childs (Malusa, 1997). Consequently, since 1916, much of the streambed has been nearly dry except for approximately 2.8 L/s of water that leaks from the Fossil Springs dam and from runoff from storm events.

In 1994, Arizona Public Service (APS) applied to the Federal Energy Regulatory Commission (FERC) to renew their power generation license and continue water diversion from Fossil Creek, but economic and environmental concerns led to an agreement to decommission the Fossil Springs dam and restore full flows to Fossil Creek by December 31, 2004.

### *1.2. Macrophytes*

Decommissioning the Fossil Springs dam could impose substantial impacts on the ecosystems of Fossil Creek. Macrophytes have been found to provide many ecosystem services in riparian areas (Fox, 1992). In Fossil Creek, cattails, *Typha* sp., are the dominant macrophyte and provide habitat and food for algae, invertebrates, amphibians, reptiles, fish and birds (Fox, 1992; Martin et al., 1982; Payne, 1992; Soszka, 1975). Fox (1992) found increased surface area of macrophytes and the localized reduction in flows provides a substratum and refuge for epiphytic algae, invertebrates, fish and their eggs, while Gerking (1957) found greater numbers of fauna on macrophytes compared to the benthos. Sponholtz (2001) found that populations of native fish in Fossil Creek were positively associated with macrophytic or riparian cover in travertine pools. The endangered Yuma clapper rail, Red-winged blackbirds, yellow-headed blackbirds and marsh wrens use *Typha* patches as favored nesting sites (Hinojosa-Huerta et al., 2001; Martin et al., 1951).

The anticipated re-watering of Fossil Creek will alter the hydrologic regime and thus, habitats available for macrophytes. Light intensity, water depth and flow rate can be used to predict suitable *Typha* habitat (Chapter 3), which is the dominant macrophyte in Fossil Creek. This study uses these habitat parameters to create spatial models of suitable *Typha* habitat in Fossil Creek under present and future hydrologic conditions resulting from decommissioning the Fossil Springs dam.

Countless management decisions have been made during the decommissioning of approximately 200 dams in the United States (Poff and Hart, 2002). Unfortunately, most were made with insufficient information about pre- and post-dam conditions (Babbitt, 2002). Creating and testing ecological models can help quantify current conditions and predict future scenarios based upon a variety of restoration alternatives. Fossil Creek provides an excellent opportunity to test the predictive ability of spatial models. The purpose of this study is to predict the responses of ecological communities to re-watering using currently available hydrologic models, satellite and aerial imagery, digital elevation models and GIS tools.

## 2. Methods

### *2.1. Mosaic DEMs*

Digital elevation models (DEMs) were downloaded from http://aria.arizona.edu for the 4 Digital Orthophoto Quarter Quads (DOQQs) (Strawberry, Hackberry Mountain, Verde Hot Springs and Cane Springs Mountain) that represent the study area (bounded by UTM NAD 83, zone 12N, 449102.5 E, 3812325 N and 436892.5 E, 3795165 N). The DEMs for Strawberry and Hackberry Mountain were available in 10 m by 10 m resolutions, while the DEMs for Verde Hot Springs and Cane Springs Mountain were available in 30 m by 30 m resolutions. Arcview (ESRI, 1995-2001) was used to resample the 30 m DEMs and convert them to pixel sizes of 10 m by 10 m. These DEMs were then combined into a mosaic using the Spatial Tools Arcview extension. The DEM mosaic was then clipped to the bounding coordinates using Imagine (ERDAS, 2001).

### *2.2. Hydrologic model*

Arcview and the hydrologic program, HEC-RAS 3.0 (US Army Corp of Engineers, 1997) (available at http://www.hec.usace.army.mil/software/) was used with HEC geo-RAS 3.0 (US Army Corps of Engineers, 2001) GUI interface. HEC geo-RAS extrapolated 178 channel cross-sections from the DEM mosaic. Channel banks, centerline of flow path and Manning's n were input using Arcview 3.2. Manning's n was visually estimated from Phillips and Ingersoll (1997) and assumed to be 0.036 for all of Fossil Creek, but Schlinger (2003) has since estimated the roughness as being substantially greater for a different section of Fossil Creek. The channel cross-section, flow input, and flow output data were then incorporated into the HEC-RAS model for both present and future conditions (Table 4-1) following the removal of the Fossil Springs dam. Travertine dams were added to the topography to mimic the geomorphology at a future time point. These dams were placed at locations identified by Grant (Unpublished data) and were modeled as being 3 m in height. This assumption is conservative because Santos (1901) reported that the Fossil Creek travertine dams ranged from 10 to 30 feet (3.0 – 9.1 m) high. HEC geo-RAS, using the HEC-RAS output, provided spatial models of flow velocity and water depth of the entire study area under present (Figs. 4-2A and B) and future conditions (Figs. 4-2C and D).

### *2.3. False color imagery*

Landsat 7 Thematic Mapper (TM) images (Bands 1-7) were downloaded from http://aria.arizona.edu for the areas covered on path/row 36/36. The Landsat images (acquired by USGS on June 20, 1993) were then clipped to the bounding coordinates (UTM NAD 83, zone 12N, 449102.5 E, 3812325 N and 436892.5 E, 3795165 N) and resampled to 10 m by 10 m pixels using Imagine. A false-color image was then created of the study area by stacking bands 1 (blue), 2 (green) and 4 (red). Bands 1 and 2 were assigned color bands that reflect their true reflective wavelengths. Band 3 reflects red wavelengths and band 4 reflects infrared wavelengths. By assigning band 4 as red rather than band 3, the characteristic reflectance of infrared wavelengths by chlorophyll was utilized. The resulting false color image displays healthy vegetation in red hues (Fig. 4-3).

*2.4. Reclassification of canopy cover*

A true-color aerial photograph (acquired by USFS on July 13, 1998) was converted to a digital format. Using Imagine, this image was then georeferenced to the reference coordinate system (NAD 83, zone 12N) of the Landsat 7 TM band 2 image. Twelve control point locations were identified unambiguously on both the aerial photograph and the Landsat image. A second order polynomial was fit to the control points and used to estimate the position of each pixel in the georeferenced image. Pixel size was maintained at 10 m by 10 m and a nearest neighbor sampling method was used. The georeferencing root mean square (RMS) error was given as 13 m.

Using the digital georeferenced aerial photo, I examined areas without vegetation (0% canopy cover) and areas with dense vegetation (100% canopy cover) and compared the corresponding red color hues on the false-color Landsat image. The color range between these red hues was isolated on the false color image and all other colors were removed from the image by reassigning these colors to transparent. The resulting image contains pixels representing reflectance by vegetation. These color values were then reclassified into 5 categories (0 representing 80 - 100% canopy; 1 representing 60 - 80% canopy, 2 representing 40 - 60% canopy; 3 representing 20 - 40% canopy, 4 representing 0 - 20% canopy) (Fig. 4-4).

*2.5. Reclassification for habitat suitability*

A relative habitat suitability scale (Table 4-2) for *Typha* was developed in Chapter 3. This scale was used to reclassify the existing images into GIS layers that allow predictions regarding Typha habitat suitability using Imagine. The reclassified water depth and canopy cover layers were "added" together spatially for each scenario using Imagine. This layer was then "multiplied" by the binary flow velocity layer using Imagine. The resulting layer for each scenario displayed suitable habitat for *Typha* under present (low flow) and future (full flow) conditions (Figs. 4-5 and 4-6).

## 3. Results and Discussion

Several assumptions were made during the construction of my models. If these assumptions were met, then the models would be expected to perform well and the predictions would be accurate. The assumptions are as follows:

*Assumptions*

- Channel morphology is correctly estimated by low resolution DEMs.
- With a 30-m pixel resolution, no changes in canopy cover in the Fossil Creek watershed will be caused by dam removal.
- Riparian vegetation canopy is "healthy" as indicated by high reflectance in LANDSAT TM Band 4. "Healthy" vegetation being characterized by plants with low water stress.
- Each travertine dam is modeled as 3 m in height from the lowest point in the channel.
- Future travertine dams will be located at each remnant located by Grant (Unpublished report).
- Channel banks are correctly estimated from a digital topographic map for HEC-geo RAS input.
- Channel flow path is in the center of the channel for HEC-geo RAS input.
- Precipitation has no effect on the model.
- Spring base flow does not change.

The total area of suitable *Typha* habitat is modeled to be 21% greater under present flow conditions (181,100 $m^2$) than future conditions (149,700 $m^2$). Figs. 4-5 and 4-6 show large spatial differences in habitat suitability for Typha under present and future hydrologic conditions. Under present conditions, suitable habitat is found throughout the entire length of Fossil Creek; while under future conditions, suitable habitat lies only in the first 6.4 km of the stream, because this stretch was modeled to have pools with slow flow velocities, resulting from travertine dams (Fig. 4-2C). Approximately 6.4 km downstream of the springs, $CaCO_3$ no longer precipitates in the form of travertine dams because $CO_2$ concentrations in the water become equilibrated with the atmosphere (Malusa, 1997). The water velocities increase as the system changes from a pool – drop to a riffle – run morphology with flow rates greater than the maximum water velocity tolerated by *Typha* (Chapter 3).

This study also compared the habitat potential of *only* the travertine depositing section under present and post-dam removal conditions. This was done because *all* future *Typha* habitat was predicted in this section. Table 4-4 shows the amount of suitable habitat under present (low flow) and future (full flow) conditions. It is interesting to see that the area of *Typha* habitat within the initial 6.4 km is predicted to nearly triple under future conditions.

*3.1. Implications*

Re-watering Fossil Creek will change present streambed morphology and generate different habitats. Upstream of Irving, the pool-drop structure created by travertine dams will dominate the morphology; while downstream the stream will be characterized as riffle-run. Based upon my model, the Fossil Creek ecosystems will change profoundly following the decommissioning and I've made predictions about how they may look. The travertine dams will provide ideal habitat for maidenhair fern (*Adiantum capillus-veneris*) and their pools will maintain diverse emergent and riparian habitats. River alder (*Alnus Rhombifolia*), sycamore (*Platanus wrightii*), ash (*Fraxinus anomala*) and black Walnut (*Juglans nigra*) will tower overhead, while the cattails (*Typha domingensis*), bulrush (*Scirpus sp.),* watercress (*Rorippa nasturtium*) and mosses (*Fontinalis hypnoides* and *Filicinum cratoneuron*) will provide substrate for invertebrates and algae and increase siltation rates. The endangered Yuma Clapper rail and yellow-headed blackbird might nest in the cattails, while American dippers forage beneath its cover. Increasing sediments will sustain populations of tubicifids and aquatic fungi. *Potamogeton sp.* and other submergent plants will take root within the sediments, thus creating more habitats for periphyton and the invertebrates that feed upon it. This community of organisms will provide food and refuge for Leopard frogs (*Rana sp.*), Sonoran and desert suckers (*Catostomus insignis* and *clarkii)* and headwater and roundtail chub (*Gila nigra* and *robusta*).

Results of my models suggest that the reach downstream of Irving will also support a different assemblage of flora and fauna. There will be fewer emergent plants and less sediment, yet an increased riparian area. The riffle-run morphology shall support a community of algae and invertebrates that differs from that found upstream and the birds, fish and amphibians that feed on them will be different as well. I predict that the entire re-watered Fossil Creek will contain a more diverse ecosystem than is currently present.

### *3.2. Model strengths and weaknesses*

My models illustrate gross differences may occur when the Fossil Springs dam is decommissioned and natural channel processes are restored to the ecosystem. The models mimic Fossil Creek and its associated geomorphology sufficiently that interpretations can be made at a broad scale, but the resolution of the DEMs may limit the accuracy of the predictions enough that the models will skew from reality at a micro-scale. This is the biggest limitation encountered in the development of my models.

The best DEMs that were obtained had a pixel resolution of 10 m by 10 m, but 50% of the study area had a resolution of only 30 m. These resolutions do not allow for accurate approximations of the stream channel location in Fossil Creek. At 10 m resolution, the stream channel would need to be at least 5 m wide to show up as surface water on the map. However, under present conditions, the channel is often narrower than 5 m and can be little as 0.5 m wide. Thus, at the available pixel resolutions, the hydrologic models cannot achieve a high level of accuracy. This limitation also limits the habitat found by the models. Stands of *Typha* will exist on the banks of the stream at numerous locations. However, unless the habitat supporting these stands is greater than 50 $m^2$ in area, it is not recognized in these models. This imposes substantial errors on the models.

My first assumption was that my DEMs accurately approximate the channel morphology of the stream channel. If this assumption isn't met, the water velocity and water depths would be different than those predicted by HEC-RAS. Changing either of these habitat parameters could change my predictions of habitat suitability for cattails.

More research needs to be conducted at Fossil Creek, but time is running out. Some parameters that are important to monitor during the decommissioning process include, travertine deposition; changes in plant communities; native vs. invasive plant colonization of newly exposed sediment; fish, invertebrate, amphibian, avifaunal and reptile community responses; water chemistry; sediment transport; and recreational impacts. As future researchers examine Fossil Creek and this model, problems will certainly be found. The model's short comings will help reveal flaws in my assumptions and thus help advance our understanding of the functioning of the ecosystem.

Neither hydrologic condition modeled in this study has been ground-truthed. Ground-truthing is a very important aspect of model generation and can provide us with measurements of our model accuracy. Before these models are given much weight in decision-making, they should be ground-truthed so that we have a better understanding of the "real-world" implications of the decommissioning of the Fossil Springs dam.

### *3.3. Global impacts*

The models created in this study show that the hydrologic changes associated with dam installation and removal can be substantial. Increased flow rates and water depths can have significant impacts on the ecosystem by altering the habitats found within the affected watershed, thus changing the flora and fauna that utilize those habitats. This study is an example of how GIS modeling tools can be used to identify waterbodies where invasions of problem species may occur, which can assist in the effective allocation of monitoring resources (Buchan and Padilla, 2000).

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Table 4-1

Hydrologic parameters input into HEC-RAS 3.0 as present and future conditions

| Location | Flow rate ($m^3/s$) | |
|---|---|---|
| | Present | Future |
| Fossil Springs | 1.2200 | 1.2200 |
| Dam – Into channel | 0.0006 | 1.2200 |
| Dam – Into flume (to Irving) | 1.2124 | 0.0000 |
| Irving – Into channel | 0.0056 | 0.0000 |
| Irving – Into flume (to Childs) | 1.2068 | 0.0000 |
| Confluence – Into Verde River | 0.0062 | 1.2200 |

Table 4-2

Reclassified data for spatial model according to Typha habitat preferences (Chapter 3). Higher values indicate greater relative habitat suitability.

| Canopy | | Flow rate | | Water depth | |
|---|---|---|---|---|---|
| Code | Actual | Code | Actual | Code | Actual |
| 0 | 81 - 100 % | 0 | > 0.107 m/s | 0 | > 120 cm |
| 1 | 61 - 80 % | 1 | < 0.107 m/s | 2 | 0 - 40 cm |
| 2 | 41 - 60 % | | | 4 | 40 - 80 cm |
| 3 | 21 - 40 % | | | 2 | 80 - 120 cm |
| 4 | 0 - 20 % | | | | |

Table 4-3

Areas of suitable Typha habitat under present and future conditions. The difference in areas is the future minus the present, thus negative numbers are indicative of future conditions having less suitable habitat at that level.

| | Area ($m^2$) | | |
|---|---|---|---|
| Habitat Suitability | Present | Future | Difference |
| 1 | 16,700 | 26,000 | **55.7 %** |
| 2 | 73,100 | 35,700 | **-51.2 %** |
| 3 | 16,600 | 20,900 | **25.9 %** |
| 4 | 53,600 | 48,000 | **-10.4 %** |
| 5 | 7,700 | 5,200 | **-32.5 %** |
| 6 | 7,500 | 9,800 | **30.7 %** |
| 7 | 2,200 | 700 | **-68.2 %** |
| 8 - Highest | 3,700 | 3,400 | **-8.1 %** |
| **Total** | **181,100** | **149,700** | |

Table 4-4

Subset of suitable Typha habitat areas under present and future conditions found in the travertine depositing section of Fossil Creek at full flows. The difference in areas is the future minus the present, thus positive numbers are indicative of future conditions having more suitable habitat at that level.

| | Area ($m^2$) | | |
|---|---|---|---|
| Habitat Suitability | Present | Future | Difference |
| 1 | 4,900 | 26,000 | **431 %** |
| 2 | 13,600 | 35,700 | **161 %** |
| 3 | 8,500 | 20,900 | **146 %** |
| 4 | 18,000 | 48,000 | **167 %** |
| 5 | 3,300 | 5,200 | **58 %** |
| 6 | 4,100 | 9,800 | **139 %** |
| 7 | 1,000 | 700 | **-30 %** |
| 8 - Highest | 2,600 | 3,400 | **31 %** |
| **Total** | **56,000** | **149,700** | |

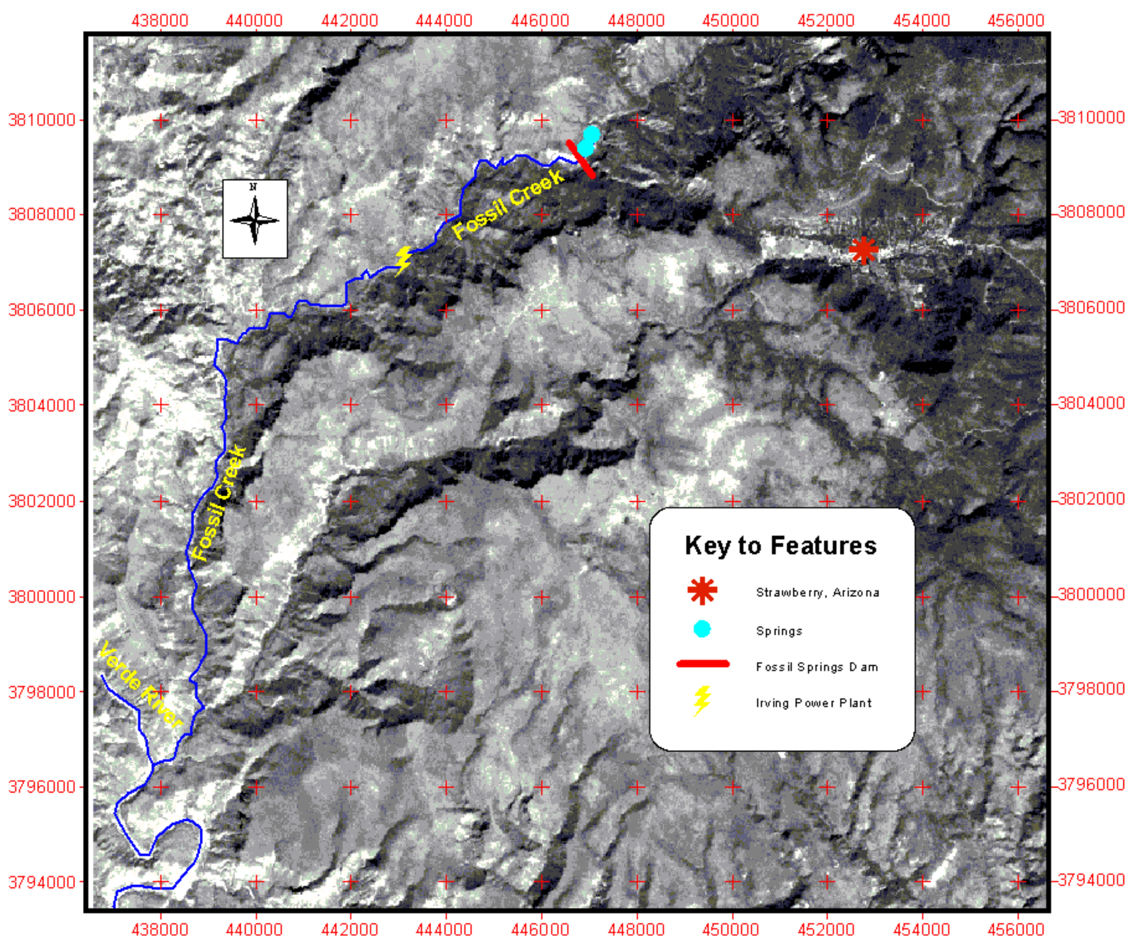


Fig. 4-1. Map showing Fossil Creek study area. Map created by Chas Jones on 5/27/2003 using Arcview 3.2. Projection: UTM NAD 83, zone 12N.

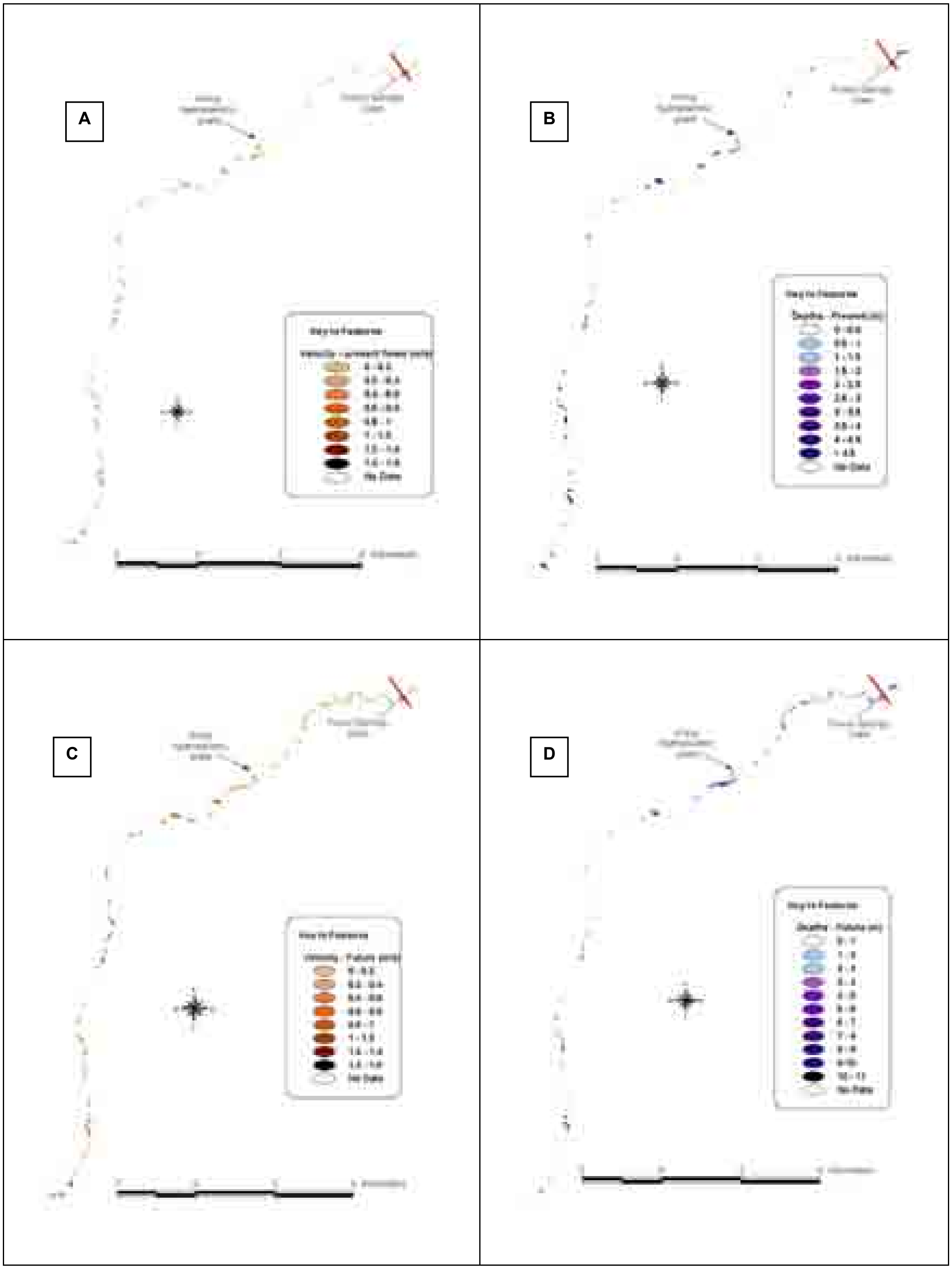


Fig. 4-2.  Spatial models of (a) present water velocity, (b) present water depth, (c) future water velocity and (d) future water depth in Fossil Creek.  Maps created by Chas Jones on 12/27/2002 using Arcview 3.2.  Projection:  UTM NAD 83, zone 12N.

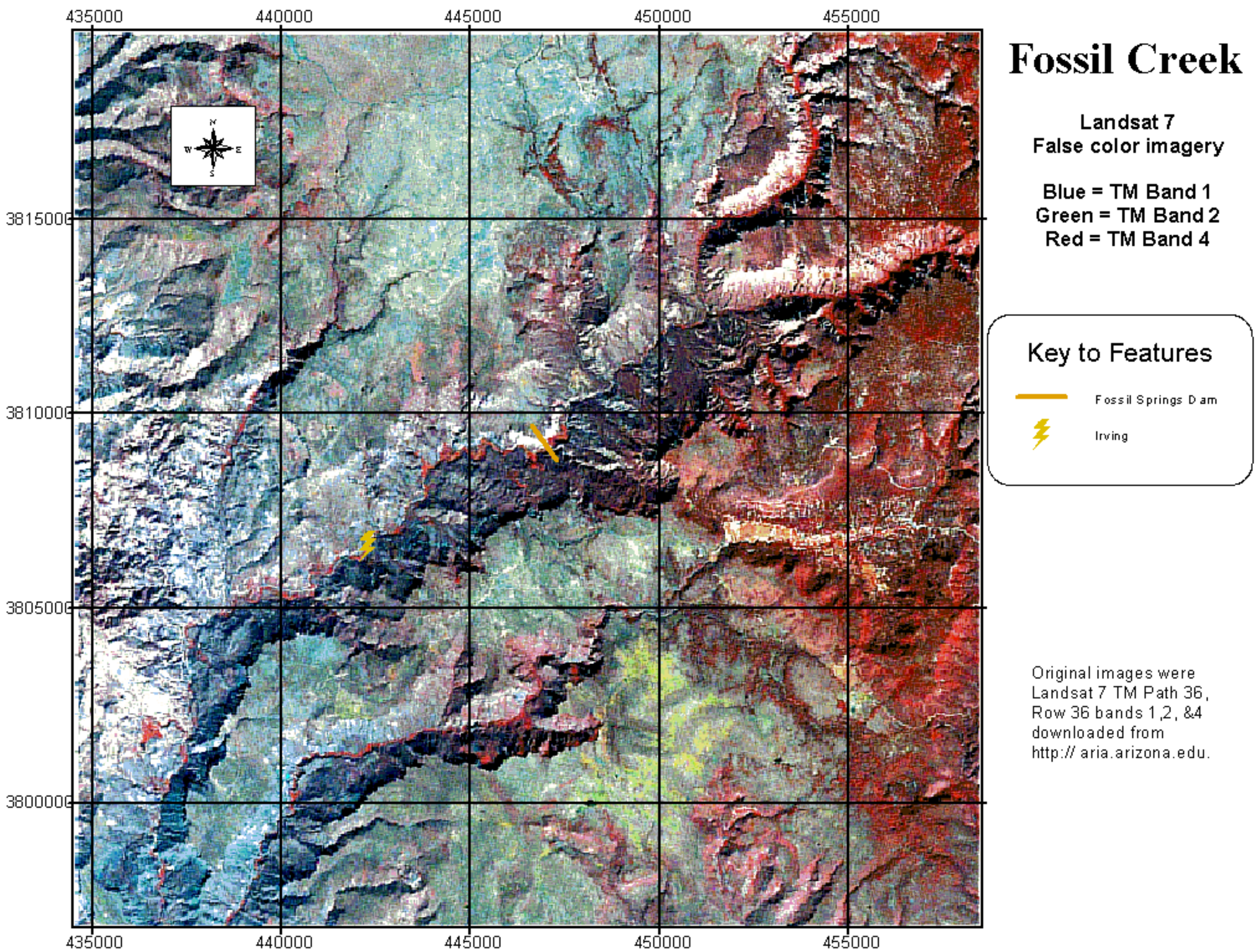


Fig. 4-3. False-color image of Fossil Creek. Red hues are indicative of vegetation. Created by Chas Jones on 7/13/2002 using ERDAS Imagine. Projection UTM NAD83, zone 12N.

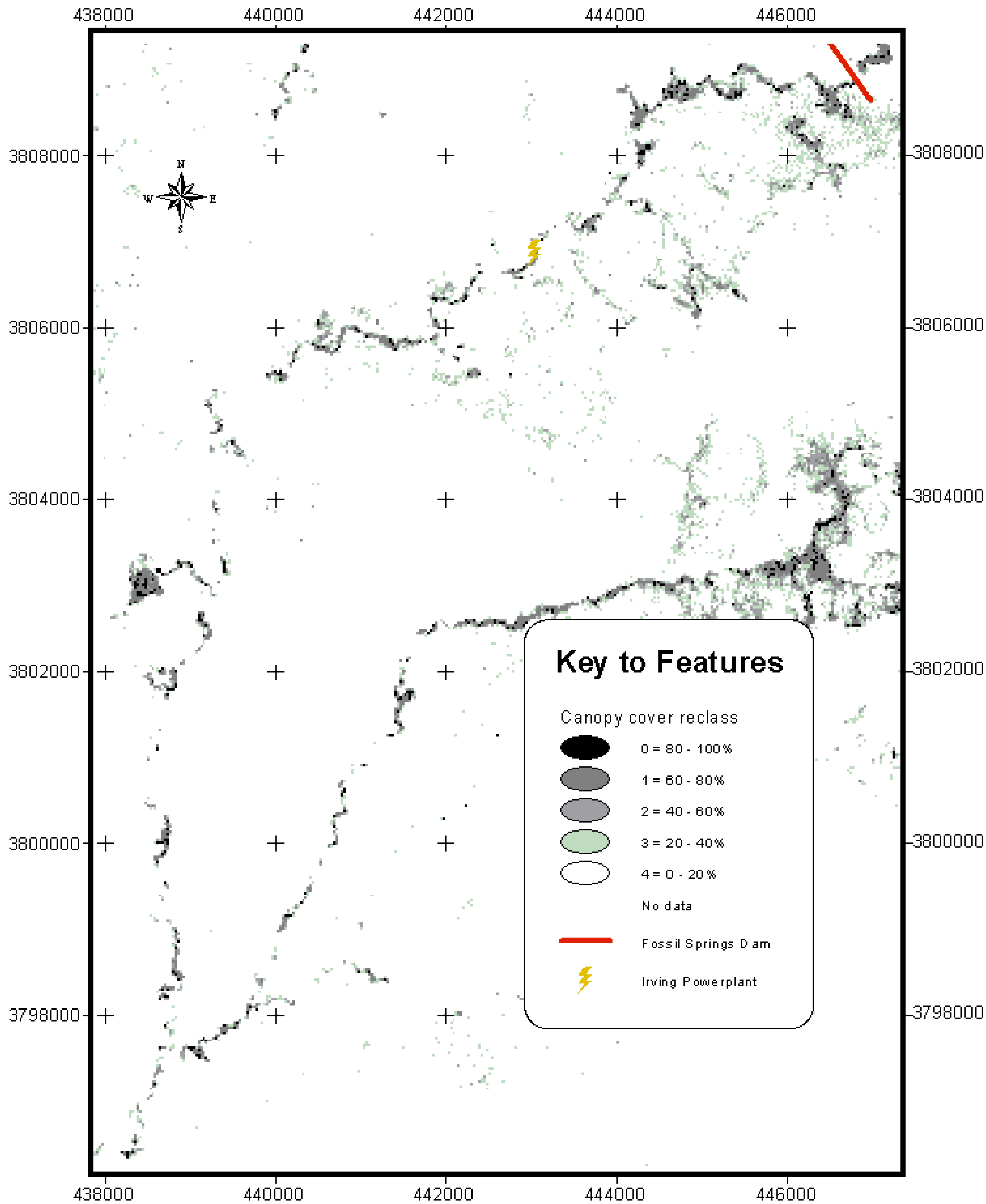


Fig. 4-4. Canopy cover derived from the false-color image and a geo-referenced aerial photograph of Fossil Creek. Created by Chas Jones on July 15, 2002 using ERDAS Imagine 8.5. Projection: UTM NAD 83, zone 12N.

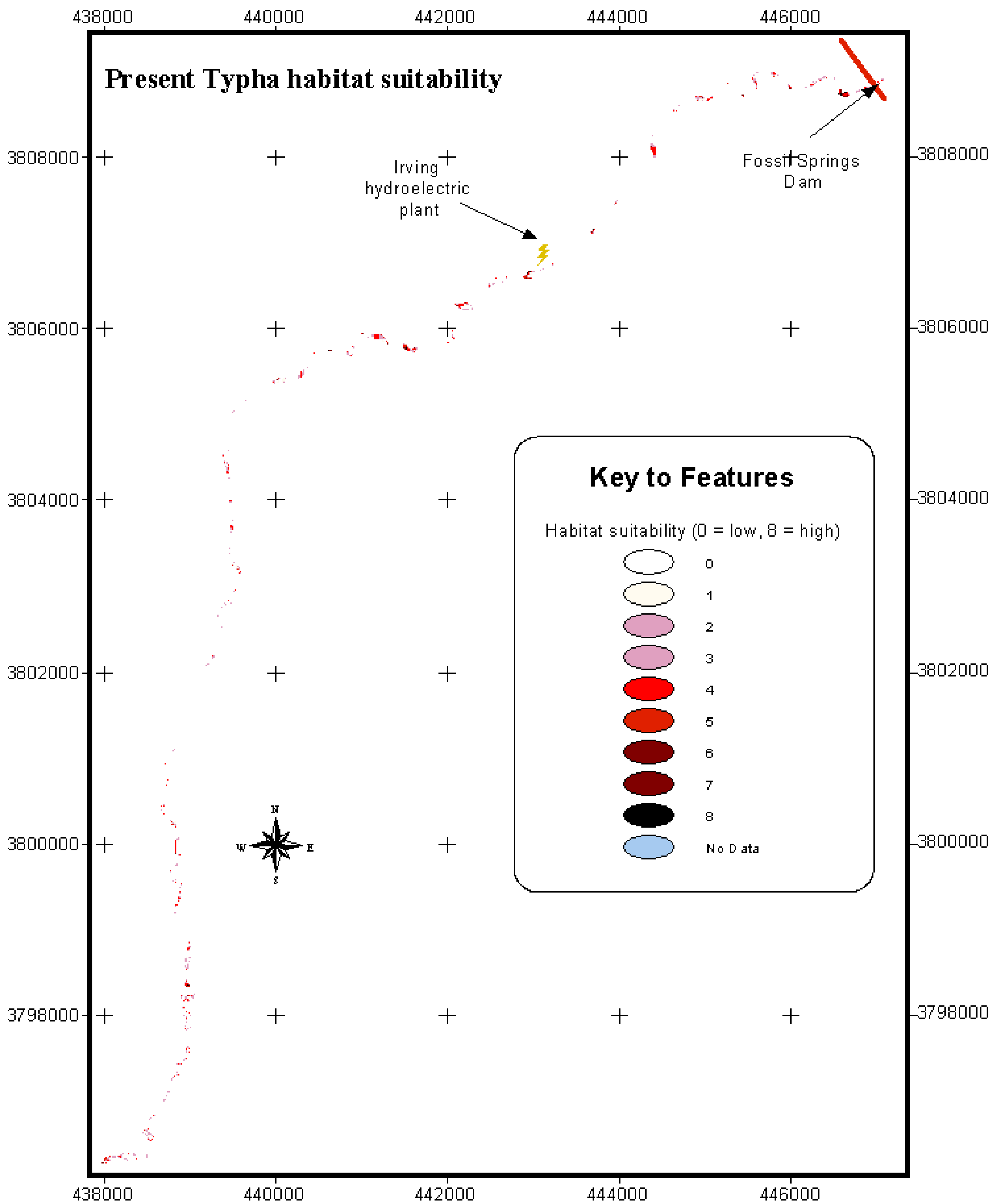


Fig. 4-5. Spatial model of present habitat suitability for *Typha* in Fossil Creek. Created by Chas Jones on July 15, 2002 using ERDAS Imagine 8.5. Projection: UTM NAD 83, zone 12N.

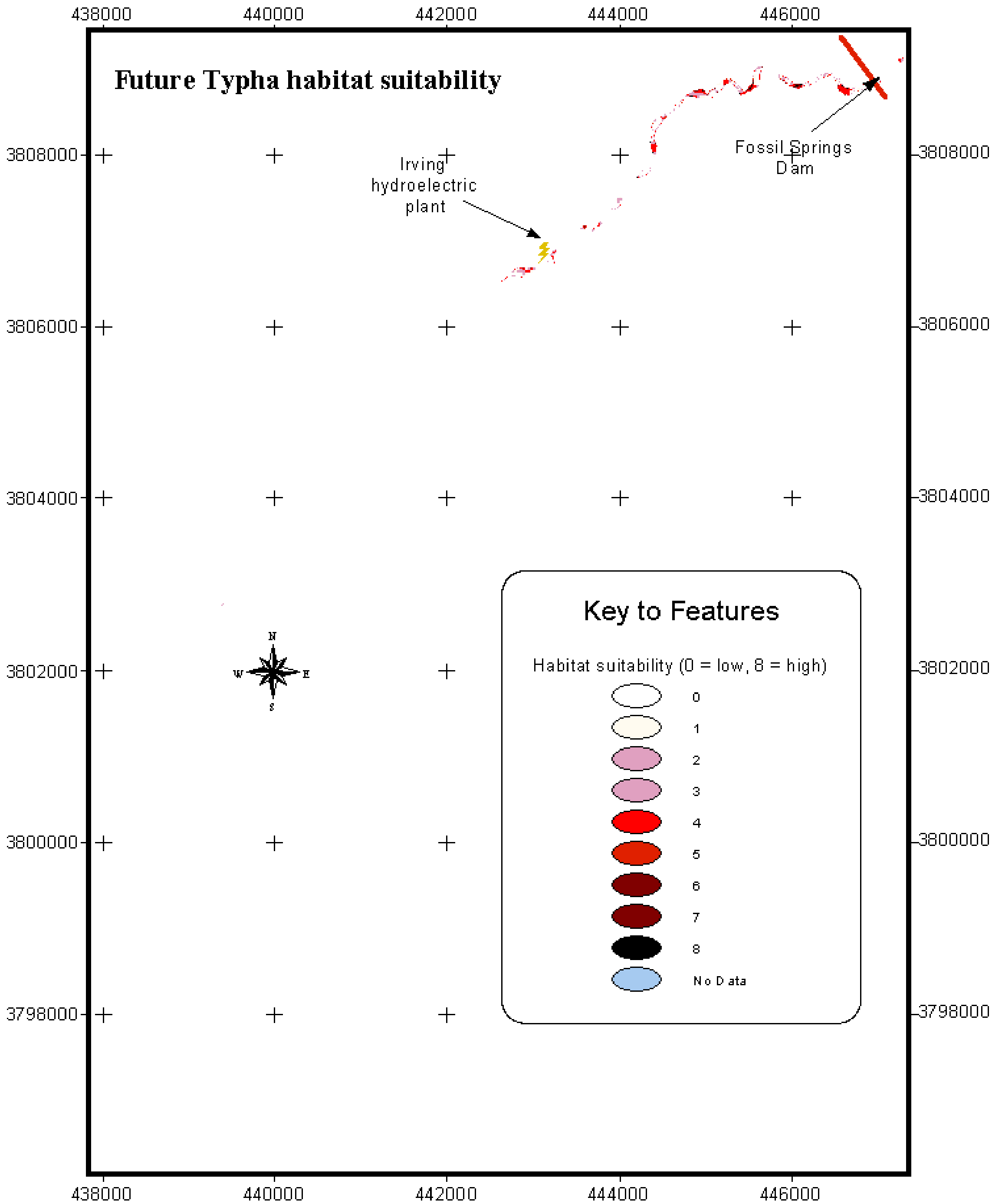


Fig. 4-6. Spatial model of future habitat suitability for *Typha* in Fossil Creek. Created by Chas Jones on July 15, 2002 using ERDAS Imagine 8.5. Projection: UTM NAD 83, zone 12N.

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## CHAPTER FIVE

## CONCLUSIONS

Decommissioning Fossil Creek dam provides an opportunity to state a restoration target and attempt to reach that target. In chapter one, I propose that the restoration goal for Fossil Creek should be to recreate the creek's natural structure and function by reinstating key ecosystem patterns and processes. I made the following recommendations to help us reach that target:

- Return of the full 1218 L/s to the stream channel, allowing the characteristic travertine dams to develop and offer a structurally complex channel,
- Removal of the top 6 feet of the dam, and
- Amelioration of recreational impacts by establishing designated parking areas, trails, picnic areas, restroom facilities and camping sites

In chapter three, I examined how *Typha* modifies and creates habitat for other organisms. I suggested that *Typha* slows the water velocity of the water traveling through it and sediments accumulated within *Typha* patches. I also determined that light intensity, water velocity and water depth could be used as predictors of *Typha* habitat under maintenance conditions and developed a habitat suitability scale for these parameters.

In chapter four, I examined how the geomorphology of the stream channel and the habitat provided macrophytes might change following the re-watering of Fossil Creek. I showed that the water velocity would slow substantially through the travertine depositing reach of the stream. As a result, *Typha* habitat is limited solely to the travertine depositing reach of the stream. I also found that the total area of *Typha* habitat would be reduced under future flows when compared to present flow conditions.

These results are evidence that stream conditions change significantly when dams are installed. The presence of dams in our watersheds has detrimental environmental and social impacts that are often not recognized. As our demands for renewable power sources increase, alternative energy sources will be tapped, but those that have the least ecological impacts should be favored. The ecological impacts of anthropogenic activities need to be identified and ameliorated before humans can sustainably co-exist with the ecosystems upon which our survival relies.

## APPENDIX A

## LOCATIONS OF TRAVERTINE DAMS IN FOSSIL CREEK, ARIZONA

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Data provided by Joe Grant, unpublished report

Projection: UTM NAD 27, zone 12N

| Travertine Dam # | **Easting** | **Northing** | River Station location of Travertine dam |
|---|---|---|---|
| Diversion Dam | 447128.96 | 3808879.89 | 23075.00 |
| 1 | 447081.76 | 3808931.90 | 23004.77 |
| 2 | 447147.86 | 3808791.96 | 22850.00 |
| 3 | 447091.02 | 3808794.75 | 22793.09 |
| 4 | 447043.52 | 3808730.66 | 22713.32 |
| 5 | 447004.65 | 3808716.42 | 22671.92 |
| 6 | 446943.22 | 3808688.42 | 22604.41 |
| 7 | 446979.22 | 3808744.96 | 22537.38 |
| 8 | 446945.08 | 3808664.48 | 22449.96 |
| 9 | 446973.57 | 3808776.81 | 22334.07 |
| 10 | 446913.13 | 3808700.44 | 22236.68 |
| 11 | 446933.74 | 3808684.34 | 22210.53 |
| 12 | 446727.62 | 3808820.18 | 21963.67 |
| 13 | 446854.56 | 3808729.74 | 21807.81 |
| 14 | 446837.05 | 3808697.85 | 21771.43 |
| 15 | 446865.29 | 3808691.94 | 21742.58 |
| 16 | 446775.78 | 3808728.53 | 21645.88 |
| 17 | 446733.33 | 3808522.78 | 21435.79 |
| 18 | 446778.56 | 3808748.42 | 21205.67 |
| 19 | 446726.47 | 3808655.37 | 21099.03 |
| 20 | 446736.79 | 3808692.21 | 21060.77 |
| 21 | 446703.53 | 3808568.51 | 20932.68 |
| 22 | 446703.69 | 3808674.87 | 20826.32 |
| 23 | 446670.06 | 3808702.77 | 20782.62 |
| 24 | 446628.97 | 3808719.12 | 20738.40 |
| 25 | 446607.98 | 3808781.37 | 20672.70 |
| 26 | 446620.23 | 3808770.76 | 20656.50 |
| 27 | 446595.73 | 3808850.95 | 20572.65 |
| 28 | 446585.13 | 3808886.45 | 20535.60 |
| 29 | 446482.53 | 3808922.21 | 20426.95 |
| 30 | 446469.88 | 3808908.94 | 20408.61 |
| 31 | 446409.04 | 3808873.14 | 20338.02 |
| 32 | 446432.82 | 3808942.66 | 20264.55 |
| 33 | 446458.73 | 3808852.53 | 20170.77 |
| 34 | 446373.33 | 3808846.17 | 20085.13 |
| 35 | 446354.21 | 3808753.03 | 19990.05 |
| 36 | 446344.49 | 3808810.96 | 19931.31 |
| 37 | 446290.96 | 3808751.94 | 19851.63 |
| 38 | 446235.18 | 3808794.12 | 19781.69 |
| 39 | 446217.60 | 3808767.25 | 19749.58 |

| Travertine Dam # | **Easting** | **Northing** | River Station location of Travertine dam |
|---|---|---|---|
| 40 | 446151.46 | 3808743.58 | 19679.34 |
| 41 | 445961.94 | 3808815.14 | 19476.76 |
| 42 | 445869.59 | 3808859.86 | 19374.15 |
| 43 | 445834.03 | 3808901.75 | 19319.20 |
| 44 | 445804.48 | 3808911.98 | 19287.93 |
| 45 | 445781.72 | 3808926.98 | 19260.67 |
| 46 | 445717.48 | 3808911.56 | 19194.61 |
| 47 | 445662.88 | 3808900.05 | 19138.81 |
| 48 | 445644.11 | 3808879.77 | 19111.17 |
| 49 | 445638.43 | 3808845.54 | 19076.48 |
| 50 | 445618.12 | 3808845.10 | 19056.16 |
| 51 | 445637.23 | 3808824.47 | 19028.04 |
| 52 | 445592.01 | 3808625.26 | 18823.76 |
| 53 | 445601.53 | 3808615.84 | 18810.37 |
| 54 | 445471.83 | 3808654.36 | 18675.07 |
| 55 | 445475.16 | 3808610.25 | 18630.83 |
| 56 | 445443.29 | 3808753.36 | 18484.22 |
| 57 | 445441.73 | 3808741.00 | 18471.76 |
| 58 | 445350.24 | 3808720.85 | 18378.08 |
| 59 | 445201.84 | 3808807.48 | 18206.24 |
| 60 | 445188.00 | 3808699.56 | 18097.44 |
| 61 | 445408.47 | 3808590.58 | 17851.50 |
| 62 | 444999.56 | 3808663.52 | 17436.14 |
| 63 | 444861.63 | 3808589.96 | 17279.82 |
| 64 | 444839.21 | 3808602.02 | 17254.36 |
| 65 | 444802.65 | 3808613.12 | 17216.16 |
| 66 | 444803.93 | 3808639.15 | 17190.09 |
| 67 | 444813.13 | 3808552.07 | 17102.53 |
| 68 | 444790.14 | 3808481.44 | 17028.25 |
| 69 | 444756.86 | 3808257.82 | 16802.17 |
| 70 | 444769.52 | 3808500.11 | 16559.55 |
| 71 | 444800.07 | 3808486.82 | 16526.23 |
| 72 | 444701.80 | 3808453.27 | 16422.39 |
| 73 | 444593.59 | 3808407.54 | 16304.92 |
| 74 | 445571.64 | 3808387.69 | 15326.67 |
| 75 | 444598.71 | 3808233.42 | 14341.58 |
| 76 | 444575.28 | 3808271.40 | 14296.96 |
| 77 | 444441.44 | 3808134.55 | 14105.54 |
| 78 | 444460.74 | 3808247.00 | 13991.44 |
| 79 | 444493.53 | 3808215.92 | 13946.26 |
| 80 | 444488.33 | 3808164.15 | 13894.23 |
| 81 | 444402.91 | 3808192.83 | 13804.13 |

| Travertine Dam # | **Easting** | **Northing** | River Station location of Travertine dam |
|---|---|---|---|
| 82 | 444390.32 | 3808117.21 | 13727.47 |
| 83 | 444458.18 | 3808077.12 | 13648.65 |
| 84 | 444441.57 | 3807898.36 | 13469.12 |
| 85 | 444471.48 | 3807847.18 | 13409.84 |
| 86 | 444550.51 | 3807867.24 | 13328.30 |
| 87 | 444495.96 | 3807798.81 | 13240.79 |
| 88 | 444504.06 | 3807736.60 | 13178.06 |
| 89 | 444558.44 | 3807768.81 | 13114.85 |
| 90 | 444456.01 | 3807753.18 | 13011.24 |
| 91 | 444464.73 | 3807736.54 | 12992.45 |
| 93 | 444327.68 | 3807691.63 | 12848.23 |
| 94 | 444236.58 | 3807678.82 | 12756.23 |
| 95 | 444193.41 | 3807627.68 | 12689.31 |
| 96 | 444269.20 | 3807522.83 | 12559.94 |
| 97 | 444138.90 | 3807613.84 | 12401.00 |
| 98 | 444038.40 | 3807611.98 | 12300.48 |
| 99 | 444048.38 | 3807590.42 | 12276.72 |
| 100 | 444061.40 | 3807552.26 | 12236.40 |
| 101 | 444072.73 | 3807566.08 | 12218.53 |
| 102 | 444068.28 | 3807516.01 | 12168.27 |
| 103 | 444043.45 | 3807513.62 | 12143.32 |
| 104 | 444071.00 | 3807372.01 | 11999.06 |
| 105 | 444031.38 | 3807330.76 | 11941.86 |
| 106 | 444065.98 | 3807333.52 | 11907.15 |
| 107 | 444015.97 | 3807306.84 | 11850.47 |
| 108 | 443848.99 | 3807352.54 | 11677.35 |
| 109 | 443983.35 | 3807288.29 | 11528.42 |
| 110 | 443922.26 | 3807078.98 | 11310.37 |
| 112 | 443800.77 | 3807047.69 | 11184.92 |
| 113 | 443814.75 | 3807039.96 | 11168.94 |
| 114 | 443752.91 | 3807004.26 | 11097.54 |
| 115 | 443811.00 | 3807144.08 | 10946.13 |
| 116 | 443743.85 | 3807041.33 | 10823.39 |