DESIGNING AND IMPLEMENTING A LONG-TERM MONITORING PLAN FOR A DAM DECOMMISSIONING AT FOSSIL CREEK, ARIZONA

By Nathan Daniel Schott

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Approved:

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Roderic A. Parnell Jr.,
Ph.D., Chair

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Abraham E. Springer, Ph.D.

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Martha E. Lee, Ph.D.

ABSTRACT

DESIGNING AND IMPLEMENTING A LONG-TERM MONITORING PLAN

FOR A DAM DECOMMISSIONING AT FOSSIL CREEK, ARIZONA

Nathan Daniel Schott

Essential in the social and economic development of this nation, the harnessing of water resources has relied heavily upon the construction of dams. Until recently, this utilitarian view of our water resources has been widely supported. Scientific investigations into the affects dams have on aquatic and riparian ecosystems have helped to realize the consequences of dam construction. The recent realization of dams' detrimental effects coupled the fact that numerous dams are nearing the end of their structural lifetimes, means that removal is becoming an increasingly popular fate for dams in the United States.

To fully understand ecosystem response to dam decommissioning and removal activities, the scientific community has called for long-term, detailed monitoring programs to accompany dam removal projects. Many in the scientific community have advocated that an interdisciplinary approach to research and monitoring can provide a better understanding of ecosystem response than more traditional, reductionist approaches.

This thesis evaluates one interdisciplinary research team's approach to investigate ecosystem response to dam decommissioning activities on a travertine-depositing stream at Fossil Creek, Arizona. From this evaluation many important lessons have been learned about conducting interdisciplinary research in this particular context. One objective of this thesis is to synthesize the lessons learned by interdisciplinary researchers and develop a collaborative research model to improve the effectiveness of collaborative, interdisciplinary approaches to research and monitoring on future dam decommissioning projects.

As stream morphology will likely respond to decommissioning activities in profound ways, and because changes in stream morphology will drive changes throughout the entire ecosystem, monitoring stream morphology is arguably the most important monitoring need in programs accompanying dam removals. A second objective of this thesis is to evaluate the methodology used to monitor changes in streambed and channel morphology adopted by the interdisciplinary research team at Fossil Creek, AZ. While the physical surveying methodology does have some shortcomings, the methodology employed is sufficient to detect changes in stream morphology as they occur in response to dam decommissioning and removal activities.

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PREFACE

This thesis is comprised of four chapters. Chapter I contains introductory material on dams in the United States, Fossil Creek, AZ and the Fossil Creek Ecosystems Studies Group at NAU. Chapter I also contains a significant portion of the literature review conducted for this thesis. A more specific literature review is presented in the initial sections of Chapter II. This includes pertinent background information needed to understand the development of the collaborative research model presented in the final section of Chapter II. Because this chapter contains more policy-orientated material, and because portions of Chapter II will be submitted as a manuscript to be published, citations have been formatted as endnotes. All other chapters have used the citation style described by University of Chicago Manual of Style Author/Date system. Chapter III contains more traditional scientific writing, including explicit results and discussion sections. The final chapter presents some conclusions and suggestions for future research.

Chapter I. Introduction

Dams in the United States

"With increasing pressures from population growth in the West, water now is and will continue to be, the economic, environmental, and social issue of the twenty-first century" (Cronin, 2005). More specifically, management of water resources and the use of dams have recently been at the forefront of water issues in the western United States. Until recently, the construction of dams as a means of river management has been widely supported (Heinz Center, 2002). The benefits reaped from dams are numerous and have contributed significantly to the development of this country, both economically and socially (Doyle et al., 2003; World Commission on Dams, 2000). Dams provide flood control allowing for development of productive alluvial soils on river floodplains (Poff and Hart, 2002) while at the same time creating pristine waterfront properties (Born et al., 1998). Dams have created lentic environments which support large populations of sport fisheries and provide other recreation opportunities for millions of people (Born et al., 1998). They provide a reliable source of water to the millions of Americans living in the semi-arid West. The development of storage reservoirs to capture spring runoff has been essential for agricultural development, urban population growth, and the development of industry in the American West (Goodwin et al., 1997).

The formation of deep canyons due to geologic uplift and subsequent river erosion in the western United States has facilitated the construction of major hydroelectric power generating stations (Goodwin et al., 1997). These hydroelectric power plants provide a cleaner and cheaper alternative to power generation than traditional uses of fossil fuels (Bednarek, 2001). These power plants provide Americans with approximately 10% of their total electrical power (Heinz Center, 2002), and in some parts of the Pacific Northwest, as much as 82% of total electrical power (Pernin et al., 2002).

Rivers have historically been viewed as an engine for economic development, not only in the United States, but worldwide. The World Commission on Dams (WCD) considers that the purpose of any dam project must be the sustainable improvement of human welfare (WCD, 2000). This 'sustainable improvement of human welfare' seems to be the justification held by citizens and policy-makers for the construction of millions of dams over the past century.

In the United States, the attitude of using rivers as a means of economic gain is historically preserved in this nation's laws. The Wisconsin Milldam Act of 1840 encouraged the development of hydropower to fuel the state's economy (Stanley and Doyle, 2002). The US Congress passed numerous versions of the Flood Control Act throughout the 20th century, authorizing the construction of thousands of dams across the United States.

Many dams in the Southwestern United States have been the direct responsibility of the United States Bureau of Reclamation (USBR). In July 1902, Secretary of the Interior Ethan Allen Hitchcock established the United States Reclamation Service (USRS) within the Division of Hydrography in the United States Geological Survey (USGS) (USBR, 2007). After separating from the USGS in 1907, the USRS was renamed the Bureau of Reclamation (BOR) in 1924 (USBR, 2007). From the early 1900s to the late 1960s, thousands of dams and other water projects in the western United States were developed by the BOR. Today, the BOR provides one out of five western farmers with water, is the largest electric utility in the seventeen western states, operating 58 hydropower plants, and is the nations largest wholesale water supplier, administering 348 reservoirs with a total storage capacity of 245 million acre-feet (Rowley, 2006). "Nearly 30 million people all over the West depend on Reclamation projects for their municipal, industrial, and domestic water supplies" (Rowley, 2006). Construction of dams has been essential for the BOR to store and distribute water across the arid western United States.

Because scientific studies examining the consequences of dam construction were not fully recognized, or because the anticipated benefits simply outweighed the anticipated consequences, dam building had reached its pinnacle in the United States in the 1960s; in fact, "over one quarter of all American dams date from a single decade; the 1960s" (Graf, 2003). By the 1970s, many of the most economic sites for dam construction had been taken, and dam construction became much more expensive because the federal government was no longer willing to pay the entire cost of construction (Reisner and Bates, 1990). Since 1980, the federal government has built almost no new dams; the money spent has gone to finishing long-authorized projects (Reisner and Bates, 1990).

The National Inventory of Dams (NID) 2005 publication lists 79,777 structures over two meters in height with impoundments greater then 61,000m^3 (50 acre-feet) or structures greater then 7.5 meters in height with impoundments of 18,500m^3 (15 acre-feet) or more (NID, 2005). Smaller dams not included in the national inventory are more difficult to count but have been suggested to number close to two million (Born et al., 1998). The area inundated by all large reservoirs [> 108 m^3] worldwide, is comparable to the size of California (Dynesius and Nilsson, 1994).

Environmental Impacts of Dams

The past five decades have seen a shift in the attitudes and values of the American people. Americans seemed to become more environmentally conscious of their actions. This can be seen with the passing of laws such as the National Environmental Policy Act (NEPA), the Clean Water Act and the Endangered Species Act, all of which were designed to stop degradation of the nation's streams and rivers and protect the aquatic species that depend on them (Bowman, 2002). Many other wildlands protection laws have been passed, reflective of this changing attitude (e.g. the Wilderness Act in 1964, the Fish and Wildlife Coordination Act in 1965, the National Historic Preservation Act in 1966, and the Wild and Scenic Rivers Act of 1968).

With increased attention to the natural environment came the realization that dams are not the cure-all that they were once believed to be. The adverse ecological affects of dam construction are numerous, and only recently have been documented (Dynesius and Nilsson, 1994; Poff, 1997; Camargo and Voelz, 1998; Born et al., 1998; Bednarek, 2001; Poff and Hart, 2002; Hart et al., 2002; Richter et al., 2003; Pizzuto, 2002; Doyle et al, 2003; Marks, 2007). Scientists have determined that the construction of dams can reduce biodiversity and thwart ecosystem integrity due to a changing stream morphology and alteration of hydrologic regimes, not only of impounded reaches but entire river systems (Doyle et al., 2003). Dams interrupt the connectivity of the river system (Pollard and Reed, 2004) and change the quality of the water released from the reservoirs (Born et al., 1998). Dams reduce the connectivity of a river with its floodplain and limit the transfer of nutrients, sediment and organisms between terrestrial and aquatic systems (Bednarek, 2001). Altering the release of floodwaters and the altered temperature of that released water may thwart growth or migration cues (Bednarek, 2001). The turbines of power generating facilities can kill aquatic species or cause unnatural pressures which lead to increased mortality (Lutz, 1995). Dams block migration patterns of andromonous fish and alter spawning habitat by trapping fine sediment behind reservoirs. "By changing the flow of water, sediment, nutrients, energy, and biota, dams interrupt and alter most of a river's important ecological processes" (Ligon et al., 1995). Undoubtedly all of the impacts of dams on aquatic ecosystems are not yet realized.

Dam Removal

The recognition of all of these factors adversely affecting aquatic ecosystems has led to a search for solutions. One of the proposed solutions is the removal of dam structures and restoration of the associated ecosystems (Poff, 1997; Bednarek, 2001; Hart and Poff, 2002; Stanley and Doyle, 2002; Doyle et al., 2003).

"Today there is a huge and conflicting set of management objectives established by law, supported by public values, and expressed by the demands of interest groups. With many legitimate objectives, there is no single right answer to the question of how to manage a landscape" (Wondolleck and Yaffee, 2000). This disparity between management objectives becomes obvious when considering regulated rivers. Dams have been constructed to regulate the timing and quantity of flows, while most restoration objectives seek to eliminate, or at least minimize all human influences on the system. While there may be no 'right' way to manage river systems, dam removal has become, and will continue to be a popular management technique.

Dam removal in the United States is a relatively recent phenomenon (Figure 1). While several dams have been removed because of safety and economic reasons, recently environmental concerns have been the most commonly cited reason for removal (Pohl, 2002) (Figure 1). "The recent escalation of dam removals for environmental reasons is the outcome of a number of scientific, social and environmental policy changes in recent decades" (Pohl, 2002), and correlates well to the recent realization of the many detrimental ecosystem effects dams can cause.

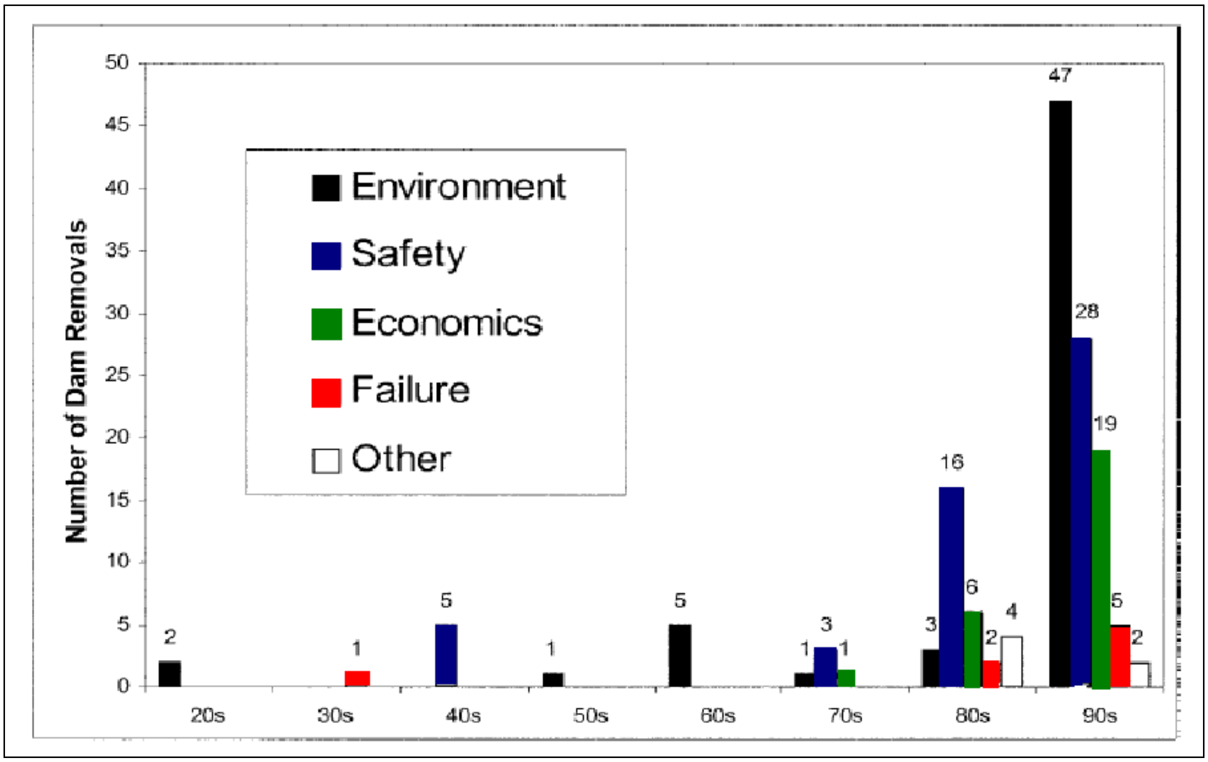

Figure 1. Number of dams removed in the United States over the past century, and the reasons cited for those removals. (Figure modified from Pohl, 2002)

Dam removal is becoming a hot topic in river management due not only to the changing attitudes and values held by the general public, but also because of the relicensing required by all hydropower dams not owned by the federal government

(Bowman, 2002). When the 30-50 year license expires, dam owners must reapply for a license through the Federal Energy Regulatory Commission (FERC) pursuant to the Federal Power Act, US Code title 16, sec. 808 (Bowman, 2002). The "FERC must then determine if issuing a new license is in the public interest, providing equal consideration for power development and nonpower uses of the river (e.g. fish and wildlife habitat, recreation, aesthetics)(US Code, title 16, sec. 797[e])" (Bowman, 2002). This relicensing process, in combination with the changing attitudes of the American public, may lead to a process in which many dams are required by the federal government to be removed.

Reservoir sedimentation may be a more important factor determining future dam removals. Most dams in the eastern United States were constructed for flood control purposes and do not require licensing by FERC. Because reservoirs slow the velocities of rivers, the suspended load is reduced and sediment accumulates at the bottoms of reservoirs. Sedimentation in reservoirs has been shown to reduce the economic benefits of projects by reducing the storage capacities of reservoirs and requiring preventive measures to keep sediment from entering intake works (Palmieri et al., 2001). Eventually the accumulated sediment can reduce the economic benefits of a dam to the point where continued operation of the dam becomes economically unfeasible.

Another factor determining future dam removal decisions is that dams have a limited structural lifetime. "By the year 2020 more than 85% of the dams in the United States will near the end of their operational lives" (Doyle et al., 2003). Often times the costs associated with repairing a dam to keep it operational are greater than the costs of removing that dam. Born et al. (1998) compared the socioeconomic costs of repairing several dams in Wisconsin with the costs of removing the dams and found that "the estimated costs of repairing a dam averaged more than three times the cost of removal."

Monitoring Dam Removals

If restoration of degraded systems is the objective, is dam removal really the best technique? The process of dam removal can potentially cause severe environmental degradation and further reduce ecosystem integrity to unrecoverable levels (Marks, 2007). That is why there is a great need for both short-term intensive monitoring of removal processes and long term studies of the ecosystem recovery process. After all, "…the central justification for removing dams from an environmental prospective is that they adversely impact the structure and function of river ecosystems" (Poff and Hart, 2002). It does not make sense to remove a dam if the removal process will further degrade the functioning of aquatic and riparian ecosystems.

Although dam removal is a proposed solution to the problems that dams have caused, and one that has increased in popularity, it has received relatively little study nationwide (Heinz Center, 2002). The removal of dams has been a fairly uncommon phenomenon in the United States with less than 500 documented dam removals (Heinz Center, 2002). This is less than 1% of the total number of dams, although this figure may be significantly higher due to undercounting (Heinz Center, 2002). More importantly, of these 500 removals, the vast majority of these have been relatively small structures, less than 5 meters in height (Heinz Center, 2002). This is important because the effects of small dams on aquatic ecosystems may be markedly different than the effects of larger dams (Hart et al., 2002; Poff and Hart, 2002). The subsequent study and monitoring of the effects of the removal process on aquatic ecosystems is something that has received even less attention (Doyle et al., 2003). As of 2002, of the 500 removed structures less than 5% of these have been accompanied by published ecological studies (Hart et al, 2002).

Who should be responsible for the monitoring? Doyle et al. (2003) suggest that because dam removal is not fully supported by enough science to validate it as a viable means of ecosystem restoration, the agency responsible for the dam removal has the burden of proof to show the efficacy of the removal. But due to budget constraints of these agencies, post-removal monitoring is often sacrificed. Another potential source of monitoring efforts can be through academia. Since dam removal is a relatively new practice incorporating many different scientific disciplines, academia is well suited for the challenges required of a well designed dam removal monitoring program. However, funding these efforts remains a challenge.

Bruce Babbitt, the former Secretary of the Interior and an authority in the construction of dams and their removal claims there is a “critical need for strong science, not just to predict what will happen when dams are removed but also to monitor dam removal outcomes so that we can learn how to maximize the effectiveness of this restoration method” (Hart and Poff, 2002; Babbitt, 2002). He claims dam removal is seen as a cure-all to the problems associated with river impoundment much in the same way as dam construction was seen as a cure-all to water supply issues, flood control and energy needs in previous decades. By jumping into removal projects without careful planning and without fully understanding the consequences of dam removal, we may be degrading our aquatic and riparian ecosystems even further (Babbitt, 2002).

Other experts in the field of dam removal, including Hart and Poff (2002), agree by stating that "future dam removal decisions can be enhanced by developing a more complete scientific understanding of the processes that determine how rivers are affected by different types of dams and how they respond to dam removal." This call for 'a more complete scientific understanding' of how dam removal will affect river ecosystems seems to be a central theme among the literature pertaining to dam decommissioning. Jim Pizzuto (2002), another expert in the field of dam removal states that "future research programs should be designed to provide the scientific knowledge to guide management decisions so that informed choices can be made as to whether dams should be removed, and if so, how, when and where." He also suggests that "our greatest need is to improve the ability to develop conceptual models that will indicate the relevant processes controlling the evolution of the river following dam removal" (Pizzuto, 2002). Through the development of conceptual models, better planning of what dams should be removed and what methods should be employed will be accomplished. Equally as important is the timing of when these dams should be removed so that the adverse affects of the removal process on river ecosystems can be minimized.

Dam removal and river restoration projects and their subsequent monitoring efforts tend to focus on organisms and neglect functional processes of the river system (Ward et al., 2001; Ligon et al., 1995). Much focus has been placed on biological aspects of riverine systems because the effects on biota are usually the final point of environmental degradation in rivers (Norris and Thoms, 1999). Legislation such as the Water Pollution Control Act of 1972 (PL 92-500) and its charge to "restore and maintain" biotic integrity has played a large role in focusing research and monitoring efforts on biological aspects of aquatic systems (Karr, 1991). The US Environmental Protection Agency (EPA) has also included biological criteria in its water quality standards program, further reinforcing this focus on biology (Norris and Thoms, 1999).

Statement and Significance of Problem

As stated above by Hart and Poff (2002), the focus of monitoring efforts should be on understanding the functional processes that will be affected by dam removal. It can be assumed that ecosystem structure and functional processes are going to drive changes in aquatic and riparian populations. By studying ecosystem processes in conjunction with changes in populations, a deeper understanding of ecosystem function can be accomplished and the science of dam removal can progress. This can only be accomplished through detailed monitoring of how different ecosystem processes respond to decommissioning and restorative activities and how they will affect both ecosystem structure and the dynamics of the populations within that ecosystem.

Each dam removal project, if accompanied by adequate monitoring efforts, will help to prevent further ecosystem degradation, and will help to validate certain decommissioning and restoration techniques. If adequate post-removal monitoring is not conducted, then the successes and failures of that project cannot be learned and that removal experience will provide little assistance in shaping ensuing removal projects.

Due to the complex nature of studying ecosystem response to dam removal, traditional reductionist research and monitoring programs may not allow for an adequate understanding of ecosystem response to be achieved. Reductionist research designs divide understandings of ecosystem response into traditional scientific disciplines. Thus, understandings of ecosystem response are limited to disciplinary understandings. While ‘bottom-up’ reductionist approaches are likely to be useful in elucidating reasons for impacts, more holistic, ‘top-down’ approaches that assess ecosystem structure and function are likely to be the most informative (Norris and Thoms, 1999). What is needed, and what has been called for by many in the scientific community is a holistic, ‘top-down’ interdisciplinary approach to research and monitoring (Goodwin et al., 1997; Wood and Armitage, 1997; Pickett et al., 1999; Naiman, 1999; Eigenbrode et al., 2007).

This thesis is a response to that call. It proposes a framework that seeks to overcome the barriers to collaborative, interdisciplinary research and monitoring, and ensure that the best approaches to understanding ecosystem response to decommissioning activities are realized. The collaborative, interdisciplinary approach to research and monitoring advocated in this thesis can result in a much deeper understanding of ecosystem response to dam decommissioning activities than traditional, discipline-based approaches.

Even if the most thorough understandings of ecosystem response to decommissioning activities are achieved by an interdisciplinary research and monitoring program, problems arise when disconnect exists between researchers and resource managers. A critical component of any successful monitoring program is effective interaction between the scientists monitoring natural resources and the personnel charged with managing those resources. Scientists need to provide monitoring data which can help resource managers to be more effective. Not only must monitoring data be applicable to management objectives, but these data must address variables which managers can control or can affect.

Many difficulties arise when designing and implementing research and monitoring programs surrounding complex issues such as dam decommissioning and river restoration projects. For any research and monitoring project to be successful, appropriate monitoring criteria must be chosen. When attempting to understand something as complex as total ecosystem response to dam decommissioning and removal activities, several important monitoring criteria begin to arise due to the numerous biotic and abiotic components of aquatic and riparian ecosystems (for examples see Figure 4). Not only do the constituent components of an ecosystem have to be understood, but also the interactions between those components. While many ecosystem components deserve attention by an interdisciplinary research team, this thesis will show that one ecosystem component in particular deserves special attention. Due to the fact that dam decommissioning activities will likely alter streambed morphology, and because a changing stream morphology and composition will drive changes throughout the entire ecosystem (Kellerhals and Church, 1986), understanding streambed and channel morphology response to decommissioning and restoration techniques is a critical component of any research and monitoring program (Graf, 2005).

Unfortunately, of the handfuls of research and monitoring programs accompanying dam decommissioning projects, many have neglected to address streambed and channel morphology response to restored flows and have tended to focus only on biological aspects of the system (Ward et al., 2001). Because understanding streambed response has received little attention in past monitoring programs, and due to the complex nature of streambed and channel morphology, little is known of the most effective monitoring methodologies. This thesis proposes and tests one promising method: change-detection using repeat, georeferenced total station topographic surveys.

Research Objectives

Because very few monitoring projects have accompanied dam decommissioning projects, and because few interdisciplinary approaches to research and monitoring have been implemented, little is known about the most effective research and monitoring designs. Working as part of an interdisciplinary research team formed to determine the effectiveness of dam decommissioning activities on a travertine-depositing stream at Fossil Creek, AZ, the author evaluated this interdisciplinary effort.

The first objective of this thesis is to provide a synthesis of lessons learned by members of an interdisciplinary research team investigating ecosystem response to dam decommissioning activities. From these lessons learned, a framework for conducting successful interdisciplinary research on future dam decommissioning and removal projects is presented. This purpose of this framework is to increase the effectiveness of future interdisciplinary research designs by identifying the barriers to successful collaboration in scientific research and providing recommendations for overcoming these barriers. The development of this framework was influenced by a literature review of interdisciplinary research, collaborative and adaptive management literature, the use of collaborative processes in dispute resolution, as well as by recommendations solicited from members of an interdisciplinary research group formed to study ecosystem response to a dam decommissioning project at Fossil Creek, AZ. This framework is presented in Chapter 2 of this thesis.

The second objective of this thesis is to evaluate the effectiveness of one particular method of monitoring streambed and channel morphology response to decommissioning activities at Fossil Creek, AZ. At Fossil Creek, streambed and channel morphology is highly influenced by the precipitation of calcium carbonate and the creation of large travertine dam structures. Due to the high rates of travertine precipitation (Malusa et al., 2003), it was determined that the most appropriate monitoring methodology would be a physical monitoring methodology that could record rapid changes in dam morphology. The streambed has been surveyed and highly detailed maps have been created. Over time, the streambed has been resurveyed, new maps have been created and changes in morphology have been determined. The final objective of this thesis is to determine the effectiveness of this particular methodology, with the hope of providing valuable insight into viable methods for monitoring streambed and channel morphology response on future dam decommissioning and removal projects.

Fossil Creek Ecosystem Studies Group at NAU

The ecosystem studies group at Northern Arizona University is composed of faculty, staff and students from five different departments who have a long-term interest in the health of the Fossil Creek ecosystems. The Fossil Creek Ecosystem Studies Group set out to deepen understandings of the Fossil Creek ecosystems, collect baseline data prior to dam decommissioning, develop a monitoring program to detect changes in the health of these ecosystems throughout the decommissioning process, and to provide data and conceptual information of value to resource managers who will continue to manage the aquatic, terrestrial and recreational resources of Fossil Creek (pers. comm. with R.

Parnell, 2007). The objective of the monitoring program is to determine the impacts of the dam decommissioning process on aquatic and riparian ecosystems by assessing the status and trends of selected resources. To achieve these objectives, the Fossil Creek Ecosystem Studies Group at NAU decided that an interdisciplinary approach to research and monitoring would be most appropriate.

Members of the interdisciplinary research team included a biologist, geochemist, hydrogeologist, hydrologist, social scientist and an engineer. Each team member has had at least one graduate student working on the project as well. Individually, each researcher would gather a perspective on ecosystem response to dam decommissioning and restoration activities based upon their disciplinary expertise. Collectively, they would share their understandings, develop new hypotheses and test these hypotheses by answering interdisciplinary research questions. This was all completed in the context of attempting to understand ecosystem level response to full-flow restoration and other restoration techniques.

Additionally, the Fossil Creek Ecosystem Studies Group at NAU worked closely with the federal and state agencies charged with carrying out restoration techniques as well as the agencies and non-governmental organizations committed to monitoring the effectiveness of those techniques. The group also worked closely with the managers of the Fossil Creek hydroelectric facilities, Arizona Public Service. Working with managers helped team members to understand the management objectives for the area, and ensured that their research and monitoring would be of use to managers. Policy recommendations, as well as monitoring data continues to be shared with all interested parties, in a variety of methods, with the objective of maintaining the health and sustainability of the Fossil Creek ecosystems.

A secondary goal of the Fossil Creek Ecosystem Studies Group at NAU is to ensure that this dam decommissioning and removal project will aid in advancing the science of dam removal and that the lessons learned will help in designing future removal projects. This synthesis of 'lessons learned' will be made available to aid in similar decommissioning processes in the future.

Major funding for this interdisciplinary research group was provided by the Nina Mason Pulliam Charitable Trust. Proposals written for the Trust provided the opportunity to link individual projects and to test interdisciplinary research hypotheses. Additional funding was provided through numerous other sources, including the National Science Foundation and the Watershed Research and Education Program.

Fossil Creek, Arizona

Site Description

Fossil Creek is a major tributary of the Verde River, originating within the incised canyons of the Mogollon Rim in central Arizona. The total length of Fossil Creek is approximately 27 kilometers and drops in elevation from 2212 meters at the Mogollon Rim to 777 meters at the confluence with the Verde (Malusa et al., 2003; Monroe, 2002). Approximately one-third of the way between the head of the drainage and the confluence with the Verde, numerous springs, collectively called Fossil Springs, convert the ephemeral stream to a perennial stream providing a constant flow of nearly 1218 liters per second (45 cubic feet per second) (Marks et al., 2006; Mathews et al., 1995)(Figure 1). The springs are located within an approximately 200-300 meter reach of Fossil Creek

(Mathews et al., 1995), along the Fossil Springs fault line, 22.4 kilometers above the confluence with the Verde River (Marks et al., 2006). The fault line exposes an outcrop of the Pennsylvanian Naco Formation, consisting chiefly of limestone and mudstone (Blakey, 1990). Fossil Springs emanate from the base of the Naco Formation, at the contact with the Redwall Limestone (Marks et al., 2005a). The source of the water at Fossil Creek is rainfall and snowmelt higher up on the Mogollon Rim. The water percolates through the soil and flows through faults and fractures in sedimentary and volcanic rock units down nearly 1,000 meters before reaching the Fossil Springs complex. These springs coalesce to form the perennial reach of Fossil Creek. A more detailed description of four surveyed reaches at Fossil Creek can be found in Chapter 3.

Fossil Creek History

An understanding of the history of Fossil Creek and the ecosystems it contains will aid in understanding dam removal expectations and the development of the interdisciplinary research and monitoring program designed to understand ecosystem response to decommissioning activities.

In 1900, a rancher by the name of Lew Turner filed the first water rights to Fossil Creek and planned to use the water to generate electricity to sell to the numerous mines in the area (Steely, 2004). In April 1908, construction began on the Childs hydroelectric power plant, one of the first hydroelectric power plants in the West (Marks et al., 2005a). Due to an increase in mining activity in the area, and thus an increasing demand for power it became clear that another power generating facility was warranted. In 1916 construction began on the Irving hydroelectric power plant, located a few kilometers upstream of the Childs power plant (Steely, 2004). The source of energy

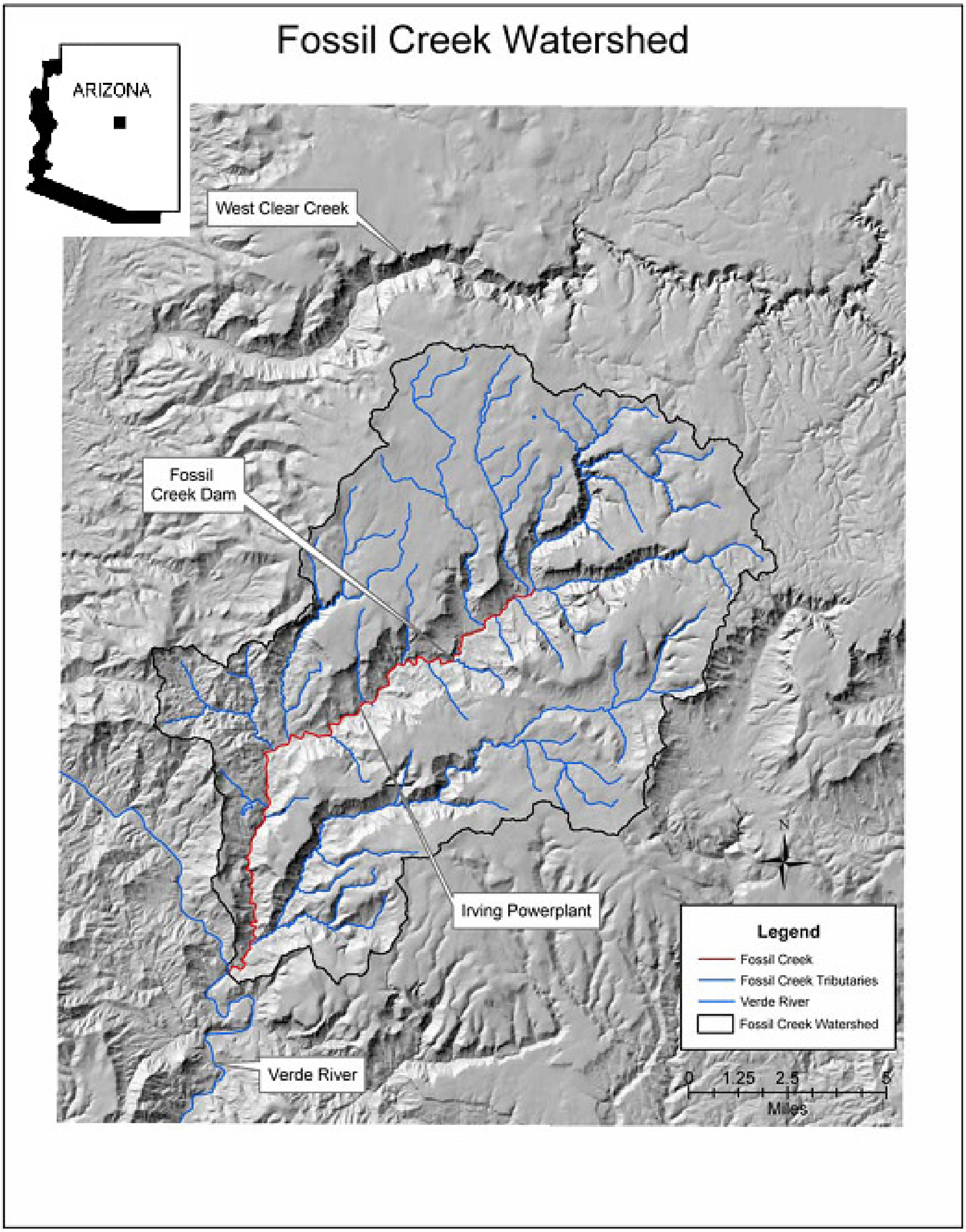

Figure 2. Map of Fossil Creek, AZ

for these two hydroelectric power plants was Fossil Creek, and the power generating facilities were designed to utilize nearly all of the 1218 liters per second of flow in the creek. For Fossil Creek to generate enough energy to effectively produce electricity, a significant drop in elevation was needed. This drop in elevation was provided by diverting all the water of Fossil Creek into a flume that ran along the valley walls. In 1909, a diversion dam was constructed to divert the waters of Fossil Creek into the flume (Steely, 2004).

The dam is approximately 8 meters high and is located 0.6 kilometers downstream of the springs (Marks et al., 2006). For the next 95 years, the majority of the water emanating from Fossil Springs was removed from the natural creek bed and was diverted into the flume that ran above the creek. Approximately 6.5 kilometers downstream from the diversion dam, the water of Fossil Creek was used for power generation at the Irving Power Plant. At Irving, between 50 and 150 liters per second of flow were returned to the natural creek bed while the rest remained in the flume (Monroe, 2002). The flume carried the remainder of Fossil Creek's water to another power generating station, Childs, approximately 17 kilometers downstream before it was released into the Verde River.

On January 1st, 1945 the Childs-Irving power generating stations were issued a 50 year license by the Federal Power Commission (Mathews et al., 1995; APS, 2004). In 1994 the owners of the dam, Arizona Public Service Company (APS) applied for a license renewal to continue operating the Childs and Irving hydroelectric generating stations (Mathews et al., 1995). As part of the renewal application an Environmental Assessment (EA) was required. Initial findings of the EA determined that restoring flows into Fossil Creek would further degrade the aquatic and riparian ecosystems. After these finding were challenged by various environmental groups and litigation was threatened, APS reconsidered the fate of the Childs and Irving hydroelectric generating facilities. On September 15th, 2000 APS requested that FERC approve the surrender of the license to operate the hydroelectric project (APS, 2004). On October 8th, 2004 APS received approval for that surrender (APS, 2007). Current plans are to lower the dam by 2.3 meters. On June 18th, 2005, full flows were returned to Fossil Creek by removing a section of the flume a couple of meters downstream of the dam.

Hydrologic Conditions

Fossil Creek is a travertine-depositing system. Travertine deposition refers to the precipitation of $CaCO_3$ out of solution and the subsequent bonding to substrates within the creek. To have travertine precipitation, the water source has to be supersaturated with respect to $CaCO_3$. The precipitation of travertine begins when percolating soil water interacts with the soil zone, carbonate aquifers, organic material or regional geothermal activity to produce H_2CO_3 (Lorah and Herman, 1988). The H_2CO_3 increases the dissolution of carbonate rocks resulting in elevated dissolved calcium and bicarbonate concentrations in the water (Malusa et al., 2003). Thus, the water emanating from Fossil Creek is supersaturated with respect to both $CaCO_3$ and CO_2. As the water discharges from the springs into the creek, outgassing of CO_2 occurs until dissolved concentrations equilibrate with atmospheric concentrations. As the outgassing occurs, a kinetic barrier is reached and the dissolved $CaCO_3$ precipitates, resulting in a form of $CaCO_3$ called travertine. If there are only calm, laminar reaches of the creek, outgassing does not occur rapidly enough to quickly surpass the kinetic barrier. This rate of outgassing of CO_2 gas increases, however, when turbulent reaches occur in the stream where water flows over rough streambed or over steep gradients, and a greater percentage of the water column is vigorously aerated. Moving downstream along turbulent reaches of the stream, travertine precipitates out of solution at high rates (Stumm and Morgan, 1981). Travertine precipitation in turbulent reaches of the stream creates structures that cause increased turbulence, resulting in a positive feedback cycle of increased turbulence and increased precipitation rates in already turbulent reaches. This causes the travertine to precipitate in restricted reaches of the stream and enhances the formation of travertine dam-like structures and related impoundments. The resulting streambed and channel morphology of a travertine depositing stream is characterized by large travertine dam structures preceded by calm, deep pools.

Factors other than turbulence can affect rates of travertine precipitation. Malusa et al. (2003) also suggest that travertine precipitation at Fossil Creek may also be controlled by filamentous green algae acting as a nucleation surface and/or a sink for CO_2. This is assumed from the diurnal fluctuations in water chemistry which is driven by biological activity (Malusa et al., 2003) and correlation between algal abumdance and travertine precipitation rates. It is the consumption of dissolved CO_2 gas by aquatic organisms that can further supersaturate $CaCO_3$ and trigger travertine precipitation.

Drysdale (1999) suggests that aquatic invertebrate species can also alter travertine precipitation. He suggests that invertebrate species that form cavities in travertine structures due to burrowing activities may increase travertine precipitation rates in four different ways: 1) the cavities act as sites for $CaCO_3$ precipitation; 2) the spinning of nets by invertebrates increases the amount of sites for $CaCO_3$ precipitation; 3) the nets and cavities increase the travertine porosity and its apparent accumulation rate, and 4) the increased surface roughness due to cavities and nets enhance $CaCO_3$ precipitation (Drysdale 1999). The load of coarse particulate organic matter (COPM) provides additional substrate where it accumulates around existing dam structures, further increasing aggradation of dams.

The formation of travertine structures is extremely important in the formation of habitat for both fish species and the invertebrate species on which they feed. Travertine also promotes the growth of algae and decomposer organisms and provides more energy to higher levels of organisms in the food chain (Marks et al., 2006). Understanding travertine precipitation rates and patterns and predicting how those rates and patterns will be altered by decommissioning and restoration techniques are of utmost importance in the development of a monitoring program accompanying dam decommissioning projects in travertine-depositing systems.

Chapter II. Collaborative Research Model

Introduction

As has been shown in the Chapter 1, research over the past few decades has concluded that dams are causing severe environmental degradation to aquatic and riparian ecosystems. A changing public sentiment regarding the use of dams, coupled with the fact that many of these structures are nearing the end of their structural and operational lifetimes means that dam decommissioning and removal will become an increasingly common management strategy. But using dam removal as a restoration technique may further impair the associated ecosystems, perhaps beyond certain thresholds to unrecoverable levels. Using the analogy of a stick, if enough stress is exerted on that stick, it will break. Simply removing those stresses does not ensure that the stick will become whole again. If enough pressures and stresses are placed on an ecosystem, including those placed on an ecosystem by decommissioning and other restoration activities, it can also break.

The scientific community has called for a better understanding of how ecosystems respond to dam removal, to assess its effectiveness as restoration technique. The biggest areas of uncertainty in ecosystem response to dam decommissioning activities cannot be answered by traditional scientists working solely within specific disciplines. What is needed is an interdisciplinary approach to further the understanding of how these ecosystems respond to dam removal; but interdisciplinary research has its challenges. "[It] requires agencies and groups to navigate the rocky shoals of human relationships, deal with problematic attitudes, do things in ways that have not been traditional, and spend limited time and effort on activities that may or may not produce benefits."[1] To overcome these challenges, a model or framework for initiating interdisciplinary research can be of assistance. It is the objective of this thesis to develop such a framework for interdisciplinary thinking on both present and future dam removal scenarios. An interdisciplinary approach can further the understanding of how ecosystems respond to dam removal and can validate certain restorative techniques.

While facilitating effective interdisciplinary research is a main objective of this thesis, it is apparent that conducting good interdisciplinary research is often quite difficult. To overcome the obstacles to interdisciplinary research and monitoring, these obstacles must first be identified. The next part of this chapter identifies the most common obstacles that prevent interdisciplinary research from actually occurring. However, simply identifying obstacles may not be enough to overcome them. In addition to the structural discipline-based obstacles systemic to interdisciplinary research and monitoring, real-life problems arise when attempting to get real-life people to work collaboratively. To address both the philosophical and the practical obstacles to collaborative interdisciplinary research, the extensive literature based on collaborative processes has been utilized. The foundations of collaborative processes, their benefits, and how they can be applied to collaborative research on dam decommissioning and removal projects is the focus of the third part of this chapter. The development of the collaborative research model presented in this thesis has also been greatly influenced by open-ended, structured interviews conducted with researchers who have been involved first-hand in the dam decommissioning and restoration of Fossil Creek. The interview methodology, as well as a summary of the tremendous insight that these researchers have provided can be found in the fourth part of this chapter. The fifth section addresses the need to evaluate collaborative research projects and offers a framework for evaluation. The final portion of this chapter provides a framework for designing and implementing a successful collaborative, interdisciplinary research project on a dam decommissioning or removal scenario.

Interdisciplinary Research

"We have not turned to interdisciplinary research on a whim, but rather because there are compelling arguments in its favor"[2]

For thousands of years, scientific learning has been dominated by reductionist thought. Reductionism theory, first described by Descartes in 1637, claims that the best way to develop an understanding of a complex system is to understand that system's constituent parts and their interactions.[3] Since the reductionist approach was first introduced, scientific thought has embraced it with wide open arms, dividing knowledge into smaller and smaller units of specialization. We recognize these smaller units, today, as scientific disciplines. Since the beginning, these scientific disciplines have been developing specific ontological and epistemological commitments, reinforcing the ideal that particular ways of understanding specific parts of the world are superior to others. Within specific disciplines, scientists share similar values, morals and norms, although these are not often discussed. Scientists within the same discipline share common beliefs on what should be studied, how it should be studied, how the results should be interpreted and the types of answers that are considered legitimate. Scientific disciplines also provide scientists with a sense of identity; they provide a framework for understanding the world and their place in it.[4] But these ontological and epistemological commitments are not widely shared across scientific disciplines. Even disciplines that are seemingly related often have widely varying commitments, identities, and understandings of the world.

For hundreds of years, reductionist approaches to scientific learning have been widely accepted as the norm, as evidenced by the widely disparate scientific disciplines now found on college campuses across the world. The ontological and epistemological commitments that researchers have made to specific disciplines further reinforce this commitment to individualistic work.[5]

But the world is interdisciplinary. The physical world is a complex entity comprising many complex systems working in unison. This is no more evident elsewhere then in the realm of ecology. The ecological problems and questions that scientists and natural resource managers now face are becoming increasingly complex.[6] What is needed, and what has been called for by the scientific community is a better approach to understanding how all the different components of a complex ecosystem relate to each other. To address these increasingly complex ecological questions, an interdisciplinary approach to research and monitoring has received a great deal of attention. It has been argued that "complexity cannot be studied with tools developed essentially for a reductionist approach."[7] The interdisciplinary approach to research and monitoring advocated in this thesis not only facilitates collaboration among the natural scientists attempting to understand the physical world, but also calls upon social scientists to exert their expertise in the recognition that all environmental problems contain a human element. Interdisciplinary approaches to research and monitoring can provide a unique ability to address the complex ecological questions and issues that surround dam decommissioning and removal.

Barriers to Interdisciplinary Research

In developing the collaborative research model presented in this thesis, much of the focus has been placed on ensuring that conducting good, collaborative, interdisciplinary research actually happens. To ensure that good, interdisciplinary research occurs, an understanding of the barriers to interdisciplinary research is required. Overcoming these barriers "entails deliberately identifying and exploring differences in the assumptions fundamental to science that are held by collaborators and are implicit or explicit in their disciplines."[8] Largely, these barriers are philosophical in nature and can be boiled down to the epistemological and ontological commitments that scientists make to their respective disciplines. Often the barriers to successful collaboration can be traced back to these epistemological and ontological commitments.[9]

Epistemology is the branch of philosophy that investigates the origin, nature, methods and limits of human knowledge.[10] Over time, scientific disciplines have developed their own acceptable ways of understanding the world. It is necessary to understand that acceptable ways of producing knowledge are not always common across disciplinary boundaries. First, the purposes, motivation and goals of conducting scientific research are not shared across scientific boundaries.[11] Some disciplines emphasize theoretical knowledge while others value a more useful application of knowledge. Also, acceptable methodologies for attaining knowledge are widely variable across disciplines.[12] For example, differences exist in identifying what data should be collected, how that data should be collected, what the acceptable means of analyzing that data are, and what interpretations are acceptable. While qualitative or anecdotal data may be acceptable in the social sciences, natural scientists may require quantitative data; and while one statistical method may be the norm in one discipline, it may be unacceptable in another. More broadly, an individual's epistemic beliefs dictate what counts as evidence, and what does not.[13] Disciplines also widely vary in how conclusions are verified, another epistemic belief. Some disciplines rely on external validity measures, consisting of successful application of results to new settings or samples, while other disciplines rely on internal validity measures, which emphasize confidence that the suggested causal links are the actual ones.[14] Still other disciplines validate conclusions partly based on measurement validity, the confidence that what was actually measured was what the researchers intended to measure.[15] "Researchers in different disciplines may study the same phenomenon but differ in their theories or explanatory models."[16] When investigating complex phenomena while collaborating with other scientists, it may not be clear which models are superior to others in particular contexts. It may be easier for scientists to maintain allegiance to known models rather than investigate which models are most appropriate in a particular context.[17] These essential fundamental assumptions of basic science have played an important role in maintaining differentiated scientific disciplines.

Equally as influential in the disparity of scientific disciplines are the ontological or metaphysical commitments that specific disciplines assume. These are the assumptions held about the nature of the investigated world, including the all-important role of human values in science. While some scientists claim that science is objective and is value-neutral, other scientists conclude that science is infused with values.[18] The fundamental assumptions of how good science should be conducted are wrapped-up in value judgments held by researchers. A failure to recognize values in science can be a significant obstacle to collaboration.

Related to the integration of values in science are beliefs about the objectivity of the natural world. Some scientists claim that the world is fully objective, independent of any perspective, while others tend to believe that the world is to some extent constructed by those who investigate it.[19] All of these assumptions have an affect on determining how good science should be conducted.

Whether scientific learning should be reductionistic in nature, or more holistic, is fundamentally an ontological commitment made by a researcher. "The challenges to cross-disciplinary research … arise out of conflicting assumptions about the nature of the world, the development and verification of knowledge, and the role of values in the scientific process. These are essentially philosophical challenges, rooted in the conceptual divides that separate disciplines."[20] For good, interdisciplinary research to occur, collaborators need to recognize their individual commitments and find a way to prevent them from hindering research. Scientists will be better able to collaborate with researchers from other disciplines if they understand the underlying assumptions held by that discipline. Realizing that these assumptions have been refined for perhaps hundreds of years and are acceptable to that discipline will aid in strengthening relationships and increasing trust between collaborators. Simple realization of these fundamental differences and assumptions can go a long way to ensure that they do not impede the success of interdisciplinary research.

The barriers to interdisciplinary research are not all philosophical in nature. Evaluations of interdisciplinary projects have shown that there are significant obstacles that cannot be boiled down to philosophical beliefs. Perhaps most importantly, it needs to be realized that language issues can undermine good, collaborative, interdisciplinary research.[21] "Disciplines employ specialized terms that can bewilder the uninitiated."[22] To further complicate things, similar terms can have different connotations across disciplines. After all, "at the heart of interdisciplinarity is communication— the conversations, connections, and combinations that bring new insights to virtually every kind of scientist and engineer."[23] If collaborators cannot effectively communicate, true collaboration cannot occur.

Evaluation of previous interdisciplinary projects has shown that failures to clarify research goals can be a barrier to successful collaboration.[24] Problems can arise when an accepted goal or problem in one discipline is simply transferred to an interdisciplinary frontier.[25] Collaborators should identify a common set of goals and should work together to achieve those goals. All collaborators working together to solve a common problem is a hallmark of success in interdisciplinary work.

"One of the most significant systemic limits of IDR is that most leading journals are disciplinary territory."[26] The newer journals that may publish interdisciplinary articles may be treated with suspicion, or at least not with the same degree of respect that comes with the longer-published, discipline-based journals, although the recent popularity of interdisciplinary research has increased the respectability of interdisciplinary work. Also, "research results take longer to publish because of the number of people and personal styles involved, and there can only be one first author."[27] Publishing can be a significant obstacle to interdisciplinary research, especially with academic institutions placing so much focus on publishing.

The organization of higher education is reflective of the commitment to independent, disciplinary thinking found in specialized scientific journals where collaboration across scientific boundaries is discouraged.[28] While interdisciplinarity has become synonymous with all things progressive about research,[29] "the problem is that we keep trying to force collaborative innovations into a structure and culture that supports individual work."[30] The time and commitment necessary to overcome language barriers and familiarize oneself with another scientific discipline distracts from one's own mastery of a single discipline[31] and pure research, where academic prestige is still highest.[32] The fact that most faculty and students continue to be located in specific disciplines rather than interdisciplinary programs, and the low number of interdisciplinary programs is reflective of academia's reluctance to embrace interdisciplinary learning.

This reluctance to embrace interdisciplinary learning is not just found in academic settings, but across many institutional boundaries. "Problems result from the institutional structure within which collaboration takes place, the ways individuals and groups think about collaboration and each other, and the manner in which collaborative processes have been managed. These obstacles affect the willingness and capacity of people in all sectors to participate in collaborative activities."[33]

It also needs to be realized that interdisciplinarity requires significant amounts of time and effort.[34] It takes time to develop an understanding of the fundamental philosophical assumptions held by researchers. Significant amounts of time are required to clarify the objectives and goals of a research program. It takes time to learn the language of other scientific disciplines and wrestle with unfamiliar literature.[35] It takes time to build trusting relationships with other researchers; the "friendship and congeniality … that is critical to success."[36] It should be recognized that time can be a barrier to interdisciplinary learning if appropriate timescales are not planned for in advance, and if formal recognition of this time commitment is not made.

Benefits of Interdisciplinary Approaches

If the challenges to collaborative research can be surmounted, an increased understanding of how ecosystems respond to dam decommissioning and river restoration techniques can be achieved. Management decisions can become more informed and the consequences of these decisions can be predicted with more confidence. "Collaboration is not an end in itself; it is one strategy for achieving more sound and sustainable resource management."[37] With a greater understanding of ecosystem response, alternative restoration techniques can be validated by the widest possible spectrum of the scientific community.

In addition to the important benefits that come from an increased understanding of ecosystem response to dam decommissioning activities, researchers themselves stand to be affected by the collaboration process. "Perhaps the greatest benefit [to researchers] is the opportunity to view issues from many and often very different perspectives. This means having to understand issues and their causes, to temper one's viewpoint with those from other disciplines, and to build a response that will produce a satisfactory solution for now and the future."[38] Interdisciplinary research can provide researchers with an understanding of the strengths and limitations of scientific disciplines.[39] It has been predicted that interdisciplinary research can enhance thinking and learning skills, and can improve higher-order cognitive skills.[40] Interdisciplinary thinking can also enlarge perspectives and horizons of participants, enhance creativity and unconventional thinking as well as critical thinking.[41] The collaborative research process may also enhance a researcher's ability to integrate and synthesize different types of knowledge.[42] If collaboration is successful, researchers may become more likely to utilize interdisciplinary approaches in future research program designs. All of these potential benefits hinge upon collaborators' abilities to overcome the numerous obstacles to interdisciplinary research.

But simply realizing all the potential barriers to successful collaboration may not be enough to overcome them. Recommendations from experienced practitioners stand to greatly increase the likelihood of successful collaboration. Better yet, evaluations of the different strategies employed in overcoming specific challenges would allow researchers to pick a strategy that best suits their needs. Unfortunately the literature pertaining to interdisciplinary research does not provide these evaluations and recommendations for overcoming obstacles. Since interdisciplinary approaches to research and monitoring are only now beginning to become popular, little evaluation has occurred. To find better strategies for overcoming barriers to interdisciplinary research, we must look to another literature base. Because many other collaborative processes have already addressed many of the same challenges experienced by collaborative research, lessons learned from practitioners of these other collaborative processes are directly applicable to interdisciplinary research.

Foundations of Collaborative Processes

'Collaborative processes,' much like interdisciplinary research, has become an almost meaningless term because it is used to describe so many different pursuits. A collaborative process can loosely be defined as a process in which two or more people work together, especially in an intellectual effort.[43] Barbara Grey, a collaboration scholar defines collaboration as "(1) the pooling of appreciations and/or tangible resources, e.g., information, money, labor, ect., (2) by two or more stakeholders, (3) to solve a set of problems which neither can solve individually."[44] Obviously this can take many shapes and forms, but the term 'collaborative process' used in this thesis has a more specific connotation. The collaborative processes described herein are focused on two very specific applications: the use of collaboration management (e.g. collaborative management, adaptive management, and adaptive governance) and the use of collaboration in resolving dispute (e.g. alternative dispute resolution [ADR], environmental conflict resolution [ECR], and environmental dispute settlement [EDS]). Collaborative processes are well-developed and have proven successful in these two specific applications.[45]

The motivation for conducting interdisciplinary research is essentially the same as the motivation behind the development of other collaborative processes. Interdisciplinary research, collaborative management and the use of collaborative processes in dispute resolution all seek to find the best solution to the problem at hand. Interdisciplinary research and collaborative processes assume that the best solution can only be realized if everyone is working together to achieve common goals.

Because interdisciplinary research and collaborative processes are founded on this common assumption, similar obstacles are encountered. The people who are involved in collaborative processes and interdisciplinary research are often not familiar with the collaborative process being used, nor are they familiar with each other. Often times, participants of collaborative processes, including interdisciplinary research, will come from very different backgrounds, will vary in their values, beliefs and understanding of the world and will thus have very different identities of themselves and their place in the world. Failing to realize the different values held by participants can lead to hostile relations between participants, and can create significant barriers to successful collaboration.

For several reasons, collaborative management and the use of collaborative processes in dispute resolution have proven extremely successful in overcoming the barriers to successful collaboration. As a result, the application of collaborative processes in these particular contexts has become extremely popular.[46] This increase in popularity has allowed for systematic evaluations of these processes by participants, proponents and critics. The evaluations have been helpful in identifying the benefits of collaboration. More importantly, systematic evaluations have proven informative in identifying obstacles and providing recommendations for overcoming them. The popularity of these processes and their resultant positive evaluations are part the rationale for why collaborative processes have been chosen to help overcome the barriers to interdisciplinary research.

Because specific collaborative processes are more popular and more developed than interdisciplinary research, many important lessons can be taken from these processes. As collaborative processes and interdisciplinary research are intimately related, many of the lessons from collaborative processes are directly applicable to interdisciplinary research. These lessons can be found in the evaluations and critiques of the various applications of collaboration. If these evaluations and critiques show that certain barriers can be overcome, a benefit of the collaborative process is established. This section of the thesis utilizes this terminology, but recognizes that achieving these benefits requires overcoming obstacles. The obstacles that must be overcome to realize the full potential of the benefits of collaborative processes are fundamentally the same obstacles that must be overcome to ensure that good, interdisciplinary research occurs.

Proponents and evaluators of collaborative processes divide the potential benefits of collaborative processes into primary and secondary benefits. The primary benefit of a collaborative process assumes that the collaboration process will result in a better outcome. Within the context of interdisciplinary research, a better outcome is an increased understanding of the system being studied. Interdisciplinary approaches to research and monitoring can also increase the efficiency and cost-effectiveness of the research and monitoring program. A discussion of how interdisciplinary approaches can increase efficiency and cost-effectiveness is found below.

Collaboration Is More Efficient and Cost Effective

Collaborative processes have received a great deal of attention in an effort to save time and money. This increase in popularity can be found in government agencies, private corporations and academic institutions alike,[47] where natural resource and environmental managers are required to do more with a static level of resources.[48] Just as users of collaborative processes in management and in dispute resolution have realized the increased efficiency and cost effectiveness of collaboration, so can users of collaboration in scientific research. More specifically, just as the use of collaboration in management can reduce mismanagement, collaborative research can reduce mismanagement as well. Significant time and money can be wasted if managers must revisit and re-create management plans every few years because management decisions were not properly informed. Collaborative management assumes that if all who are affected by a management decision have input into the decision-making process, then management decisions will be more stable and longer-lasting. That same logic can be applied to collaborative research. From an analysis of management of water resources, experts write, "[a]daptive governance also aims to resolve conflicts among competing users in a manner that enhances joint gains while minimizing negotiation costs."[49] Another expert concurs. "Adaptive governance produces 'better' resolution of water disputes because it … [is] *more efficient* – from the standpoint of independent analysis – because they produce results … while minimizing the investment of time and money required"[50] [emphasis in original]. Not only is collaborative management more efficient and cost-effective, but the use of collaborative processes in dispute settlement has also been claimed to be more efficient and cost-effective. Eliminating the need for lawyers and judges to resolve disputes can save significant amounts of time and money, because litigation is often quite expensive. "Mediated negotiation is attractive because … it produces results more rapidly and at a lower cost than do courts."[51]

Scientific evidence backs the claims of experts who note the cost effectiveness and efficiency of collaborative approaches. Chapter 2 of d'Estree and Colby's book *Braving the Currents* cite no less than six studies that have concluded that ECR is more cost effective than the alternatives.[52] Numerous additional sources conclude that ECR is cheaper and more efficient.[53] Patricia Orr offers a good compilation of more then a dozen studies comparing costs incurred using ECR to other methods.[54] She writes that "evidence from the field confirms the contribution ECR can make to resolving environmental disputes in a cost-effective manner as compared with more traditional resolution processes."[55]

Just as the use of collaboration in management and dispute resolution has increased efficiency and cost-effectiveness, so can its use in scientific research. Among the many ways in which the costs of scientific research can be reduced is the elimination of overlap in data collection. Lessons learned from the research and monitoring of water quality that occurred during the Fossil Creek dam decommissioning provide an excellent example of how increased collaboration could save time and money. It has been estimated that no less then three different research groups have been collecting water quality data.[56] As it stands now, water-quality data are being collected at different locations at different frequencies, and are being analyzed for different constituents using different methods. Increased collaboration by these three or more research groups could standardize the water-quality data being collected, having one of two effects. Either data collection could be standardized and shared among all research groups, allowing for a larger single set of water-quality data to be compiled, or the responsibility of data collection could be shared, reducing travel costs to and from collection sites, as well as the costs associated with analyzing the data.

An important lesson to be taken from this example is that methods need to be standardized before any data collection begins. If the various researchers and managers interested in water-quality data were to try and collaborate now, or anytime in the future, data collected and analyzed using a new methodology would be incomparable to at least some of the previously collected data. The collection of water-quality data is just one example of overlap in data collection that is likely to occur with the plethora of monitoring programs that arise in dam decommissioning scenarios. At Fossil Creek, data overlap has been reported in the monitoring of fish species, invertebrate species and travertine deposition rates. Eliminating data overlap through data-sharing is just one example of how increased collaboration could have made research and monitoring programs more efficient and cost effective. Collaboration can also ensure that gathered data are complimentary rather than duplicate. Sometimes data gathered by multiple methods at the same place and time can reinforce the validity of a single method.

The secondary benefits of collaborative processes are the benefits that arise simply from participation. For the purposes of this thesis, the secondary benefits that are the most applicable to collaborative research are divided into three groups. These groups include: personal empowerment and transformation, the formation of relationships, and the creation of social capital. These may not be intentional research objectives. The existence of these benefits has been demonstrated through the inclusion of specific evaluation criteria aimed at realizing these benefits and have played a large role in increasing the popularity of collaborative processes. A discussion of each of the secondary benefits and how they are applicable to collaborative research is the focus of this next section.

Personal Transformation, Empowerment and Moral Growth

When attempting to collaboratively resolve environmental conflicts, much of the focus is placed on achieving a viable solution to the problem at hand. When comparing collaborative approaches to alternatives, several important benefits other then the quality of the outcome begin to emerge. The benefits not directly related to outcome quality are dubbed secondary benefits. Secondary benefits can arise simply out of participating in a collaborative process, whether the outcome was "successful" or not. The realization of these secondary benefits has resulted from specific evaluation criteria aimed at realizing these benefits and have been important in promoting the use of collaborative processes. If the secondary benefits realized by other applications of collaborative processes can also be realized through an interdisciplinary approach to research and monitoring, they can influence the way future research and monitoring programs are conducted.

Personal transformation, often cited as one of these secondary benefits, is also referred to as personal empowerment and can take shape in a number of different forms. Individuals gain confidence and credibility by participating in collaborative processes.[57] Individuals may also learn important new skills in areas such as, negotiation, active listening, communication, and coalition-building.[58] These skills, proponents claim, help individuals to better resolve their present dispute as well as the ability to resolve future disputes. Empowerment has also promised to enhance the involvement of the disenfranchised, increase self-esteem, and improve community relations.[59] Bush and Folger state that the benefits of using mediation, a specific type of collaboration, provides personal empowerment in the form of moral growth. They claim that collaboration's greatest asset "lies in its potential not only to find solutions to people's problems but to change people themselves for the better… These changes occur because … people find ways to avoid succumbing to conflict's most destructive pressures: to act from weakness rather than strength and to dehumanize rather than acknowledge each other. Overcoming these pressures involves making difficult moral choices, and making these choices transforms people – changes them for the better."[60]

Personal transformation and empowerment can take shape in many different forms, ranging from moral growth to the development of specific personal skills. "Despite the vagueness of existing definitions of empowerment and the relative absence of theory or research on the subject, there seems to be considerable consensus about its worth."[61]

Because interdisciplinary research requires participants to work together in much the same way as other collaborative processes, these same secondary benefits can be realized with a collaborative approach to research and monitoring. The same sets of personal skills reportedly being reaped by collaborative approaches to resolving conflict are directly applicable to collaborative research. Being part of a collaborative group allows participants to hone their communication and listening skills, and gives them more experience in developing consensus-building and group-process skills. If an individual is involved in a similar collaborative research design in the future, that research would benefit from individuals already learning these important collaboration skills. These personal skills develop simply with experience; no significant barriers prevent their development.

In addition to the development of personal skills, collaborative research stands to affect scientists in a much more profound way. "Perhaps the greatest benefit (of interdisciplinary research) is the opportunity to view issues from many and often very different perspectives. This means having to understand issues and their causes, to temper one's viewpoint with those from other disciplines, and to build a response that will produce a satisfactory solution for now and the future."[62]

Collaborative research encourages scientists to think outside of their specific disciplines. The ability to comprehend another scientific discipline's understanding of a system paves the way for innovation, truly a focal point of collaboration. True interdisciplinary thinking requires moral growth on the part of the researcher to be able to think outside of traditional scientific disciplines and see the bigger picture. Unlike the honing of listening and communication skills, achieving this type of moral growth requires overcoming significant barriers.

Perhaps the most significant barrier that researchers face in tempering their viewpoint to incorporate the knowledge of other scientific disciplines is a lack of motivation.[63] In addition to learning the language of another discipline and wading through unfamiliar literature, trying to understand the epistemological and ontological commitments that specific disciplines demand requires significant time and effort. To help overcome this barrier, a source of motivation is needed and it has been recommended that a group leader, a member of the interdisciplinary research team, should provide that motivation.[64]

"The value at the heart of the transformative approach to mediation has been identified as human moral growth in two specific dimensions *together:* strength of self *and* relation to other"[65] [emphasis in original]. While the precursors of collaborative, interdisciplinary research and monitoring necessitate personal moral growth in the form of 'strengthening of self,' including thinking outside of traditional scientific disciplines and developing personal skills in negotiation, communication and active listening, to achieve the maximum moral growth that collaborative processes have to offer, moral growth in 'relation to others' must also occur. It has been argued that these newly developed relationships are the most important benefit that can be reaped by a collaborative process.[66] This is further explained in the next section.

Relationships among Research Collaborators

The formation of good working relationships is at the heart of collaboration. In collaborative research, this is especially true. To achieve the best understanding of ecosystem response, scientists need to work closely with each other to develop a deeper understanding of the complex ecosystems being studied. This deeper understanding comes from sharing knowledge and understandings of how specific disciplinary knowledge fits into the big picture. It also comes from asking and answering difficult questions that fall between disciplinary boundaries. "[Collaboration] can assist in the development of rich pools of knowledge that draw from diverse sources and provide a framework for interdisciplinary learning and problem solving."[67] During the collaboration process, relationships that cross scientific boundaries are forged. Seen in this context, the formation of these relationships is a primary objective of collaborative research. Relationships can continue long after research and monitoring have been completed, and are seen as a secondary benefit of collaborative research.

Improved relations among participants are a benefit that has been realized since the early days of collaborative processes. In 1983, Susskind and Ozawa included it on their list of criteria used to judge success in mediation and argue that the most important goal of mediation should be relationship development.[68] The personal transformation that results from collaborative processes allows participants "to draw on these positive capacities in dealing with life's problems and relating to others."[69] Another expert of collaborative processes, specifically Environmental Dispute Settlement (EDS) writes, "[p]erhaps some of the greatest ongoing benefits result from the improved communications and working relationships that grow out of the EDS collaboration."[70] The literature pertaining to dispute resolution is particularly pertinent in overcoming the barriers to trusting relationships, as hostile relations are a significant barrier in dispute resolution. In this context, much focus is placed on reducing hostility towards each other.

Within the context of collaborative *research*, conflict is not at the heart of the problem. The relationships between parties are not hostile, they simply do not exist. However, forging trusting relationships between scientists may be equally as difficult. Scientists often times will lack the respect for other scientific disciplines that is necessary for collaborative research to be effective. "Lack of trust … translates into suspicions about others' motives and methods, and even the veracity of each other's data and approaches to analysis."[71] Developing trust between scientists and reducing hostility between disputants are similar and significant challenges.

Several recommendations to overcoming relationship barriers have been suggested by dispute resolution practitioners and members of interdisciplinary research teams. Teaching participants that different viewpoints stem from different beliefs and values is important in understanding the roots of a conflict. Finding common values and using them as a starting point is one technique used to reduce hostility identified in the literature.[72] Also, teaching participants to frame their arguments in certain ways and avoid certain language can help to increase meaningful dialogue and reduce hostility. Establishing guidelines at the beginning of a collaborative effort is another strategy that has been successful in reducing hostility and allowing for trusting relationships to be developed.[73] As mentioned before, a group leader who is familiar with collaborative processes and is familiar with the best ways to frame an argument can help to overcome this significant barrier to successful collaboration.

Strategies for creating trusting relationships have also been suggested by members of an interdisciplinary research team studying ecosystem response to a dam decommissioning at Fossil Creek. Through interviews, several researchers have commented that trust has been developed between researchers simply from meaningful contact, echoing the responses found in the literature. A complete list of trust building activities can be found in the following section of this chapter.

In order for collaborative research to be successful, the scientists involved need to trust each other and have a mutual respect for each other's work. "Parties must develop coordination and trust and be able to share the information necessary to construct integrative agreements."[74] Developing this trust and mutual respect can be a significant challenge to overcome. "…[R]elationship change is a goal not only for the improved outcomes it produces, but also because of the increased likelihood for long-term success that such change reinforces."[75] "Improved relationships make it more likely that agreements will endure, new difficulties can be addressed, and agreements will be implemented"[76]

If this barrier can be overcome and trusting relationships can be forged, evaluations of collaborative processes have shown that successful collaboration allows stereotypes to be dispelled, surprise alliances to be discovered and new lines of communication to be opened.[77] Increasing meaningful dialogue between participants of collaborative research provides an opportunity for participants to demonstrate not only their personal competence, but the capabilities of their discipline. "The process of jointly working together through differences leads to rational relationships … Parties can identify with each other after increased and regular contact."[78] Also, "Collaborative processes help develop new networks and relationships among parties."[79]

The formation of trusting relationships is a necessary task of collaborative research that can result in mutual cooperation in obtaining a deeper understanding of ecosystem response to certain pressures. Future research and monitoring programs stand to be greatly affected by the creation of relationships across disciplinary boundaries. These relationships that last well into the future can create "social capital" within the scientific community, yet another secondary benefit of collaborative research and the topic of the next section.

Social Capital

Significant research and debate has surrounded the claim that collaborative processes pave the way for the creation of social capital. The most appropriate definition of social capital within the context of collaborative research comes from the International Community Foundation; social capital is defined as "the degree to which a community or society collaborates and cooperates (through such mechanisms as networks, shared trust, norms and values) to achieve mutual benefits.[80] It is the goal of this particular collaborative research model to increase collaboration among scientists to increase trust, freely exchange information, and entrench the norm of interdisciplinary thinking to achieve the mutual benefit of a better understanding of ecosystem response to dam decommissioning and other management activities. While the creation of social capital from interdisciplinary research is going to be focused within the scientific community, the larger society will also benefit from its creation, as "high levels of social capital engender norms of cooperation and trust, reduce transaction costs, and mitigate the intensity of conflicts."[81] Simply because individuals participate in a process that encourages collaboration and increased sociability, entire societies are affected in profound ways.

The creation of social capital hinges on participants of collaborative processes being somehow transformed by the process. The collective benefits explained in this paper under the titles of personal transformation, personal empowerment, and moral growth can lead to the creation of what has been dubbed 'human capital.'[82] "Human capital is created by changes in persons that bring about skills and capabilities that make them able to act in new ways. Social Capital, however, comes about through changes in the relations among persons that facilitate action … Just as physical capital and human capital facilitate productivity, social capital does as well."[83]

The two forms of social capital that are most applicable to collaborative research are information as social capital and social norms as social capital.[84] First, at the heart of collaborative research is the objective of sharing knowledge across disciplinary boundaries. Sharing knowledge necessitates the creation of information-sharing channels. These information-sharing channels may exist after a collaborative effort has been completed and the continued existence of these channels is one type of social capital.

Another goal of collaborative research is the creation of a norm that collaborative, interdisciplinary research is better than more traditional approaches. The creation and wider acceptance of this norm is the second form of social capital that is widely applicable to collaborative research. If the social capital created by participants of collaborative research is shared with colleagues and carried forward to new projects, the design of future research and monitoring programs stands to be greatly affected.

The creation of social capital is an important secondary benefit of collaborative processes, "but there is one effect of social capital that is especially important: its effect on the creation of human capital in the next generation."[85] The creation of human capital in collaborative research involves not only the development of personal skills essential for successful collaboration, but the ability to temper one's viewpoint to incorporate the knowledge of other scientific disciplines. If collaborative, interdisciplinary science can create increases in human capital within the scientific community, social capital is the means in which this human capital is passed on to other researchers. Scientists who advocate an interdisciplinary approach to fellow colleagues participating in research and monitoring of complex systems are more likely to be heard than an outsider who advocates collaborative research. Social capital describes the way in which collaborative research becomes integrated into the mainstream practices of scientific researchers.

In addition, the development of personal skills will also help to create social capital within the scientific community. If researchers can work collaboratively, remove disciplinary blinds and fuse individual knowledge with that of other scientific disciplines, then moral growth can occur. This moral growth is especially important in the creation of social capital. If enough social capital is created, then colleagues of interdisciplinary participants will be persuaded to adopt this approach. If collaborative research is truly a more effective method of understanding complex systems, it will be realized by the scientific community and passed on. For example, over a dozen undergraduate and graduate students from Northern Arizona University have participated in the Fossil Creek project, growing from this interdisciplinary effort.

Social capital is an intangible benefit of collaborative processes and is not something that proponents of collaborative research should directly strive for. Rather, it should be realized that social capital is created as a byproduct of collaboration. Evaluative criteria designed to quantify this important secondary benefit of collaborative processes have been important in the increased popularity of certain applications of collaboration, including its application to conflict resolution and collaborative management. Thus, the creation of social capital is something that should be considered when evaluating and comparing collaborative research to more traditional approaches.

Conclusions concerning the value of collaboration

To search for more efficient and cost-effective means of resolving conflict, collaborative approaches are being tried more and more frequently.[86] "Besides sharing existing information and involving and educating the public, many collaborative efforts expand understanding by generating new information and dealing with uncertainty through joint research and fact finding."[87] Through this mechanism, proponents of collaboration have claimed that collaborative approaches provide a better outcome than more traditional approaches. In addition to a better outcome, collaboration is more efficient, cost-effective and can produce numerous secondary benefits. Collaborative research is simply the application of well developed collaborative processes to scientific research and monitoring. Important lessons can be learned from these collaborative processes. The totality of benefits to be reaped from collaborative research have not yet been fully realized, but this thesis attempts to summarize these potential benefits and recommend strategies to ensure that these benefits are realized in their greatest extent possible.

Fossil Creek Researcher Interviews

The development of this thesis has been strongly influenced by interviews with the various researchers whom have been directly involved with the dam decommissioning at Fossil Creek, AZ. These interviews were essential in developing a collaborative research model not based solely on theory, but one that responds to the real-life obstacles to collaboration that come with dealing with real-life people. Through these interviews, obstacles not identified in the literature were recognized and new strategies for overcoming these obstacles have been recommended.

Interview Objectives

Interview questions were focused on understanding the degree of interdisciplinary research that was conducted, the effectiveness of that research, the obstacles to interdisciplinary research that were recognized, and the response of these researchers to those obstacles. In developing the collaborative research model presented in this thesis, the recommendations that researchers provided for overcoming the various barriers were extremely influential. The assessment of interdisciplinary research efforts by the researchers themselves proved to be the most insightful and the most influential contributions to the development of this thesis.

Interview Methodology

Two different types of scientists at Fossil Creek were identified. The first group consisted of scientists from several different federal and state agencies who have been mandated to monitor the effects of decommissioning on certain species. Some of this monitoring has been mandated by legislation such as the Endangered Species Act, while other monitoring efforts have been suggested by the managing agency to measure the success of dam decommissioning activities and ensure proper future resource management. The following entities have been either directly or indirectly involved in research or monitoring programs at Fossil Creek: United States Forest Service (USFS), Bureau of Reclamation (BOR), United States Fish and Wildlife Service (USFWS), Arizona Department of Game and Fish (AZGFD), Arizona Public Service (APS), and the Yavapai-Apache Tribe. With only one exception, all of the researchers employed by Federal and State agencies either did not respond to the request to be interviewed, or denied the request.

The second group of scientists identified were all members of an interdisciplinary research team from Northern Arizona University who have set out "to deepen the understanding of the Fossil Creek ecosystem, create a baseline assessment of conditions prior to restoration of full flows, and develop a monitoring approach to measure the success of the dam decommissioning."[88] Members of this group included a biologist, a geochemist, a hydrogeologist, a social scientist and an engineer. A geomorphologist has recently been added to the team. Each researcher also had at least one graduate student working on this project. To understand how successful the interdisciplinary approach to research and monitoring was, interviews with these five researchers and their respective graduate students were conducted.

Because interviews involved human subjects, interview methodology was subject to review by the NAU Institutional Review Board (IRB). Authorization for conducting these interviews was obtained from the Northern Arizona University Institutional Review Board on November 22, 2006. As part of the authorized methodology, all interviewees were required to sign an Informed Consent Document approved by the IRB. As part of the consent, interviewees were informed that if quotes were to be used in a printed document, a copy of the quote in its context were to be sent to the participant for approval. Additionally, names would be kept confidential. Notes were taken by the interviewer during the interview as interviews were not tape recorded. Responses were typed immediately after each interview. All information gathered during the interviews was kept in the possession of Nathan Schott throughout the duration of the study. After completion of the study, all materials are to be stored in a secure location at Northern Arizona University in Flagstaff, AZ by Roderic Parnell Jr., Ph.D.

All participants were sent a standardized email asking for permission to be interviewed. This email provided the participants with a general description of the project (Appendix A). Attached to each email was a list of potential questions to be asked during the interview. The list of potential questions was tailored for each individual. All questions were selected from a master list of potential interview questions (Appendix B).

Interviews were approached with a set of 15-20 questions each designed to elicit responses pertinent to motivating research questions. The questions were open-ended, and were not identical across all interviewees, as not all questions were appropriate nor useful to ask of all interviewees. Given the open-ended and flexible nature of the questions, discussions often diverged from pre-set questions and drifted into unanticipated directions. Discussions were generally conversational in format.

Interviews were all conducted in person by Nathan Schott starting in January of 2007, at various locations. Interview length varied considerably, with interviews ranging from 30 minutes to 75 minutes. In total, 10 interviews were conducted.

Survey Results

Interviews with researchers from the Fossil Creek Ecosystem Studies Group at NAU provided a means of realizing the lessons learned by each individual researcher. Because interviews focused primarily on interdisciplinary research, many of the lessons learned are focused on the technical challenges of conducting interdisciplinary research. Due to the open-ended nature of interview questioning, several lessons not directly related to interdisciplinary research have also been learned.

Perhaps the most important lesson that was learned from the group of academic researchers at NAU was that interdisciplinary research is difficult. Simply getting researchers who are unfamiliar with this type of collaboration together to conduct interdisciplinary research does not necessarily mean that good, interdisciplinary research will occur. Even if the researchers are determined, there are still significant obstacles to overcome.

After three years of interdisciplinary work, the success of the Fossil Creek Ecosystem Studies Group at NAU continues to be debated. While many good things resulted from the interdisciplinary approach, and success has been reported on a number of different levels, many researchers felt that the full potential of an interdisciplinary research and monitoring program was not realized.

Some of the biggest obstacles to interdisciplinary research that the researchers from NAU experienced seemed to stem from personality differences. These personality differences are a real-life obstacle that comes with dealing with real-life people. Part of the motivation for the development of this thesis stems from this very important lesson learned by the Fossil Creek Ecosystem Studies Group at NAU. It is one objective of this thesis to provide a framework for recognizing that personality differences will exist, and to provide recommendations to ensure that personality differences will not distract from the quality of research or monitoring that occurs. Because practitioners of ECR have often dealt with hostile relations between parties, many strategies for overcoming negative relations identified by ECR practitioners can be used to overcome personality differences between scientific researchers.

Another important lesson that was learned through interviews with the researchers at Fossil Creek was how trusting relationships were developed between researchers. When the Fossil Creek Ecosystem Studies Group at NAU was first created, several of the researchers had had little or no contact with the other researchers. Over the life of the project, trusting relationships were developed. Holding monthly meetings where researchers had face-to-face contact played a crucial role in the development this trust. Collaborating with data collection was another way in which trust was built, not only with the NAU researchers, but also with the federal and state agency researchers. The researchers at NAU created quarterly newsletters, drafted publications and wrote other reports where research methodologies and results were reported. The collaboration that took place in writing these reports was essential in developing trust. An open-house was conducted where the researchers shared their research and monitoring with the public. One member secured funding for the creation of a documentary, in which some team members participated. As these trusting relationships are at the foundation of collaborative research, it is important that trust-building strategies be suggested for future collaborative research projects.

Through interviews with the Fossil Creek Ecosystem Studies Group at NAU it became apparent that significant overlap in data collection was occurring. For example, at least three different researchers have been collecting water quality data at Fossil Creek. These data are being used for different purposes, are being collected at different locations and are being analyzed using different techniques. "Differences in data collection methods and analytic techniques can make it difficult for groups to combine information in useful ways."[89] Increased collaboration between these researchers stands to make data more useful across political and scientific boundaries, as well as reduce costs associated with travel and data analysis. Both of these details stand to make research and monitoring projects more efficient and cost-effective. Data overlap has also been reported with monitoring of fish and invertebrate populations, as well as with the monitoring of travertine.

In spite of some of the short-comings described above, some of the benefits of collaborative processes identified earlier in this chapter were realized by the interdisciplinary research team from NAU. Several researchers have reported personal transformation and empowerment through the increased understanding of how other disciplines conduct their research. Several members of the Fossil Creek Ecosystem

Studies Group at NAU have identified the inclusion of a social scientist as an eye-opening experience. They have reportedly developed a respect for how that type of work is conducted and have realized the importance of its inclusion. Another team member was excited to learn about what ecologists do, and how they go about conducting their research. This demonstrates that these particular researchers are experiencing at least a small part of the potential benefits of personal transformation, empowerment and moral growth.

In addition to the personal transformation experienced by the NAU researchers, their professional relationships have continued to develop. With the original Pulliam Foundation funding for the Fossil Creek Ecosystem Studies Group at NAU ending in July of 2007, several members of this group have funding in place for continued interdisciplinary work at Fossil Creek. In addition, funding is being sought to continue the existence of this unique consortium of scientists and the Fossil Creek Ecosystem Studies Group.

Interviews have also highlighted the importance of specific roles within the group. Interviewees have been particularly vocal in the importance of an organizer. It was the responsibility of the organizer to organize meetings, help write and organize reports, maintain public outreach portals and ensure that deadlines were met. The organizer has also been extremely influential in maintaining dialogue between researchers within the group, maintaining dialogue between the group and the public as well as keeping an open dialogue between scientists and managers. This role has been vital to the success of the group, as researchers are often too busy to complete these sometimes tedious tasks. Specifically, the organizer has suggested that at least 20 hours a week is necessary for an organizer to conduct these and other responsibilities at the onset of a project. As the project winds down, that 20 hours per week can be reduced. Towards the end of the interdisciplinary project conducted by the researchers at NAU, 8 hours per week has been sufficient. It is important to note that this person was paid on a grant to do exactly this; the person was not a faculty member.

The organizer has been particularly helpful in providing recommendations for improvement; the most influential of which was that a group leader is needed. Combining recommendations of the organizer and other scientists, the group leader should be a member of the interdisciplinary research team, should be someone who is well respected by the group, and more importantly, should be someone who is familiar with interdisciplinary research and collaborative processes. The role of the group leader should be to ensure that the benefits of collaborative research are realized and that the obstacles do not prevent good, collaborative research from occurring. A group leader would need to get all researchers to buy into the interdisciplinary approach. Explaining the benefits that have been realized by other collaborative processes and the potential benefits that can be realized through an interdisciplinary approach to research and monitoring would help to get all team members thinking alike. The group leader should also set ground rules and enforce them, identify sources of personality differences and aid in resolving them, keep researchers motivated about interdisciplinarity, and prevent them from falling back into disciplinary ruts. Strategies for completing these daunting tasks are provided in the collaborative research model presented later in this chapter.

While the collaborative research model focuses on increasing meaningful collaboration between researchers, increasing collaboration between researchers and managers is also very important. Interviews with scientists have identified a lack of communication between these two groups. Most scientists were unable to identify the management objectives at Fossil Creek. Moreover, many researchers at NAU identified that they were willing to modify their research or monitoring programs to help address management objectives, if they were known to them. Soliciting a more active presence of managers in a collaborative team would ensure that research results will be useful when making management decisions.

Evaluating Collaborative Research Projects

While claims by collaboration proponents suggest that collaborative research can provide numerous benefits over traditional research methods, there exists little evidence, or experience on the part of science researchers, to back up those claims. The benefits and drawbacks of collaborative research need to be described in a rigorous manner that is convincing to scientists if collaborative research is to become a widely accepted research methodology. Comparative analysis is one such rigorous methodology. Just as the use of comparative analysis has been successful in increasing the acceptability of other collaborative processes by identifying the benefits of a collaborative approach, so can comparative analysis aid in increasing the popularity of collaborative research.

Comparative analysis is the systematic comparison of evaluations of two or more things. In the context of collaborative research, comparisons can be made between the evaluations of two collaborative approaches to identify the benefits and drawbacks of subtle differences between those approaches, or more importantly, comparisons can be made between the evaluation of a collaborative approach to research and monitoring and the evaluation of a more traditional approach. Conducting evaluations and comparisons in a rigorous manner can provide the evidence that scientists require for the benefits of collaborative research to be widely accepted. These comparisons can help to identify the benefits and pitfalls of each approach in addition to deepening the understanding of how those approaches compare to each other. Because comparative analysis has been used to justify the acceptability of other collaborative processes that have now become the status quo, many important lessons can be drawn from these other collaborative processes. Recently, practitioners of Environmental Conflict Resolution (ECR) have heard the call for comparative analysis[90] and have responded overwhelmingly. Because ECR and collaborative research have been shown to be intimately related, many lessons learned by ECR practitioners regarding comparative analysis should be considered when comparing collaborative research projects.

This section seeks to identify the need for systematic and standardized evaluations of collaborative research projects, summarize some important lessons learned in other collaborative processes as a result of standardized evaluations, and present a standardized evaluative framework to be used on collaborative research projects.

Lessons Learned from the Evaluation of Collaborative Processes

One important lesson learned from the ECR literature is the critical importance of a standardized evaluation framework. "Comparative analysis, at least in its most systematic and reliable form, is possible only if cases each report on similar dimensions."[91] If a standardized evaluation framework is not used, evaluations must be created from numerous different sources including case summaries written by practitioners, interviews with participants and practitioners, opinions reported by various media sources, and many others. Often these types of evaluations are conducted long after a project has been completed and comparisons can be difficult. The problem is that "typically, case studies are written with a specific focus for a specific audience…"[92] "…most case analyses typically are done through the particular lens of their author, and thus few case reports have information on comparable variables."[93] While much information can be found on one aspect of the case, often very little information can be found on other aspects. "For one to make any comparisons among cases in order to draw larger lessons becomes almost impossible, as one is forced to compare case documentations that are, figuratively, apples and oranges. For true comparison, cases must document similar criteria."[94] This problem is likely to be the same for collaborative research.

The ECR literature demonstrates that a standardized evaluation framework should be developed.[95] Collaborative management literature has also claimed that "being inflexible about criteria used to evaluate the performance of units or individuals … has been problematic."[96] The use of standardized evaluations provides a rigorous framework that identifies criteria of successful collaboration, how those criteria should be measured, and ensures that equal attention is paid to all criteria.

Standardized evaluation criteria should be developed for collaborative research projects. These standardized evaluations are necessary for comparative analysis to identify the benefits and shortcomings of each collaborative research project. Early recognition of the shortcomings of collaborative research will allow these shortcomings to be fixed before they occur on a broader scale. Comparative analysis allows for modification and optimization of best research designs, but few of these comprehensive evaluations have been conducted. Evaluations can also aid in determining the appropriate circumstances for collaborative research, the effectiveness of collaborative research, and how collaborative approaches compare to more traditional approaches.

While comparative analysis can identify the benefits and pitfalls of collaborative processes, its primary use is to aid in increasing the acceptability of collaborative research. One important lesson to note is that collaborative processes face an uphill battle in overcoming the status quo to become the norm. There is tremendous power found in defending the status quo.[97] Just as other collaborative processes have become popular with practitioners, so can collaborative research become popular with scientists; but popularity will not come easy. Because science is based upon the collection and verification of evidence, the scientific community requires more proof of the value of collaborative research than that required by practitioners of other collaborative processes. Designing evaluation criteria to demonstrate the numerous benefits of collaboration is one lesson learned from practitioners of other collaborative processes who used comparative analysis, and is a lesson that is especially pertinent to collaborative research.[98] Understanding the criteria developed to evaluate success of other collaborative processes will help in developing criteria used to evaluate success in collaborative research. Another important lesson learned from ECR's use of comparative analysis is that evaluation criteria must not focus solely on the outcome, but on the process itself if the all-important secondary benefits of a collaborative process are to be realized.[99]

The development of a standardized evaluation framework for ECR projects has identified several criteria to be used to document project success. "Using several strategies including reviewing multiple literatures, interviewing practitioners and researchers, and drawing from evaluation work in related fields, [the authors] worked empirically to assemble a comprehensive list of the varying ways that 'success' in conflict resolution has been conceptualized."[100] As a result, many different measures of evaluating ECR and other collaborative projects have been incorporated into one single framework.

The framework presented in *Braving the Currents*, by Tamra Pearson d'Estree and Bonnie G. Colby has been influential in the development of a standardized evaluation framework for collaborative research. The framework expands from evaluations focused just on the outcome to include evaluation of the benefits of the collaborative process itself.

Standardized Evaluation Framework for Use on Collaborative Research Projects

One way to give collaborative research the best possible chance of becoming an acceptable methodology within the scientific community is to use a standardized framework to evaluate collaborative research projects. The development of this evaluative framework has been adapted from an evaluation framework used on ECR projects, developed by d'Estree and Colby.[101]

Both the framework developed by d'Estree and Colby and the one proposed in this thesis have divided evaluation criteria into several conceptual categories. "Conceptual categories can be useful tools for framing and considering further questions, such as: What does this categorization tell us about underlying dimensions or assumption about the goal and practice of [collaborative research]? Do categories suggest [evaluation] criteria that may be missing?"[102] For each conceptual category, the specific evaluation criteria is identified, methods for measuring these criteria are suggested as well as when the best time to assess criteria is. This last point is important as over time, perceptions and attitudes about certain aspects of a process or an outcome may change. The three conceptual categories used in the evaluation of collaborative research projects include: outcome quality, relationships between researchers, and the creation of social capital.

Outcome Quality

The first category of criteria is *Outcome Quality*. The outcome of a collaborative research project will be the understanding of the system being studied. In addition to determining the level of understanding that was achieved, this category strives to evaluate certain aspects of the outcome itself, including clarity of the outcome, cost-effectiveness, and economic efficiency.

Obviously, the most important evaluation criteria in outcome quality will be an assessment of the achievement of research objectives, as well as an assessment of the level of understanding that was achieved by participants of a collaborative research project. Quantifying the degree of understanding can be a difficult task. Conceptual understandings can be useful, but hard to quantify. Predictive, quantitative models can predict changes with a certain degree of confidence. This confidence is something that can be compared across interdisciplinary efforts.

Evaluating this criterion should come from two sources. First, understanding the level of interdisciplinary work that actually occurred is necessary. This understanding can come from an outsider review of the papers that have been published and the reports and newsletters that have been written. The nature of these products, either disciplinary or interdisciplinary will tell a lot about the degree of success of the collaborative effort.

Additionally, interviews with researchers themselves can provide insight into the level of understanding achieved. Potential questions include: How confident are you in the understanding you have achieved? How does the level of understanding achieved compare to the level of understanding achieved on other research projects you have been involved in? Do you think a collaborative research design allows for a greater understanding to be achieved? In addition to these questions being asked of researchers, very similar questions should be asked of managers. Because managers frequently follow scientific research related to their management concerns, their opinions can provide tremendous insight into the quality of understanding that has been conveyed by researchers. These interviews should be conducted shortly after a research program has been completed, while that program is still fresh in the minds of the researchers and managers. The evaluations of papers and reports can be conducted anytime after a research program is completed, but it should be kept in mind that it can sometimes take several years for certain papers to be published.

Evaluating the depth and resolution of the understanding of the system is another evaluation criterion that should be addressed. Not only should the achievement of research objectives be evaluated, but if these research objectives contributed significantly to an increased understanding of ecosystem structure and function. If there are widely varying degrees of confidence in the understanding of the system being studied, this is an indication that collaborative research may not be providing the best outcome. A hierarchy of understanding needs to be developed. The most basic understanding includes identification of an ecosystem's biotic and abiotic components. Conceptualizing the interactions between these components is a higher degree of understanding while quantifying these interactions is an even higher degree of understanding. The development of predictive models that quantitatively explain variances in all of the ecosystem's components is perhaps the best understanding that can be achieved. Again, this criterion should be assessed through interviews with researchers involved with the project shortly after a research program has been completed.

Assessing the cost-effectiveness of a research program is another outcome quality evaluation criterion. Because proponents of collaborative research have claimed increased efficiency and cost-effectiveness, these claims need to be verified. Assessing this criterion requires gathering budget information from all researchers. A tallying of all the money spent over the life of a research program can provide a basis for comparative analysis, although simply comparing budgets of two different research or monitoring programs is unlikely to provide useful comparative data. This assessment can be completed anytime after the budgets of the researcher or monitoring program have been set.

Comparing costs may not provide useful comparisons. Research programs come in many different shapes and sizes, but even comparing research programs of similar sizes may not be appropriate. What can be useful is comparison of perceived economic efficiency of interdisciplinary approaches to more traditional research approaches. Assessing the perceived economic efficiency takes into account not only program size, budget and level of understanding achieved, but also asks if the cost were justified by the benefits. Perceived economic efficiency is based on whether the collaborative research outcome creates net benefits (benefits minus costs) that would not be available otherwise.[103] As many of the benefits of collaborative research cannot easily have a dollar amount assigned to them, economic efficiency focuses on perceived costs and perceived benefits. These benefits and costs should be assessed by researchers, through interviews, shortly after a research or monitoring program has been completed.

<u>Relationship between Researchers</u>

The second category of criteria is *Relationship Quality,* or the relationships that exist between researchers. Assessing relationship change can measure some of the secondary benefits of collaborative processes, and can be divided into four specific evaluation criteria: improved relations, cognitive and affective shift, ability to work together on future research designs, and personal transformation.

The improved relations criterion seeks to capture changes in the way parties see and relate to one another, as relationship change may reflect the essence of successful collaboration.[104] To assess this criterion, many different sources should be used. First, assessments from the researchers themselves can provide insight into how relationships have changed. These assessments can be conducted as part of an interview, or can be interpreted through correspondences between researchers. Also, media sources, public outreach portals, speeches, and third party reports can all be analyzed for specific language identifying relations between parties. A change in the tone of communication can be indicative of a change in relations between parties. Trust can also been inferred from a lack of formalities placed on researchers. The authorship of publications, proposals, and presentations, whether joint or individual authored, can be indicative of relationship change. The timing of assessment of relationship change should be conducted early on in the process, for baseline purposes, and again upon completion of the research or monitoring program.

Cognitive and affective shift is another secondary benefit of collaborative processes that will likely be reaped by a collaborative research design. The ability to understand the underlying values required by specific scientific disciplines, and to prevent differing values from impeding the quality of interdisciplinary research are both characteristic of a cognitive and affective shift. The ability to temper one's viewpoint by incorporating the knowledge of other scientific disciplines and to see the bigger picture is one of the most profound cognitive shifts that a scientist can experience.

Because cognitive shifts are not usually noted in others, self-reflection provides the most likely source of realizing these important changes. If possible, baseline interviews should be conducted so that self-reflective questions can elicit responses for a cognitive baseline. Upon completion of a research program the same questions can be asked again, and cognitive shifts can be realized. If cognitive shifts are noted in others, these may take the form of individuals noting that issues are framed differently, attitudes change, behavior is described differently, that there are changes in how individuals think, and changes in how individuals view themselves within the group as well as their interdependence. These changes may all be indicative of a cognitive and affective shift. These changes may be reported in newsletters, internal party documents, correspondences between researchers, or may be solicited in interviews. The assessment of cognitive shifts should be conducted upon completion, or near completion of the research program.

If collaborative research is successful, relationships that were forged across disciplinary boundaries can endure. These enduring relationships can have profound affects on the design of future research and monitoring programs, increasing the likelihood that a similar approach will be utilized again. The effectiveness of future collaborative research programs will also be increased as the burden of developing trusting and respectful relationships need not be overcome again. The ability of researchers to work together on future research projects is indicative of successful collaboration and should be included on the list of evaluation criteria. Even if researchers do not work together on future research projects, changes in the nature of future research efforts (i.e. becoming more interdisciplinary and cooperative) can indicate a change in a researcher's ability and willingness to work collaboratively.

To assess researchers' ability to work together on future research projects, significant follow-up efforts may be required. Follow-up efforts should take the form of researching what projects the researchers have been involved with after the research project being evaluated. Interviews provide an easy way of gathering all relevant materials for evaluating this criterion. Obtaining all papers and reports published by a researcher, and cross-referencing those for participants of past collaborative efforts provides another, albeit more difficult way in which this criterion can be evaluated. Analyzing co-authors can indicate changes in an individual's ability and willingness to work collaboratively. This criterion should be evaluated after an appropriate amount of time has passed for future research endeavors to be completed and published.

Personal transformation is another claimed secondary benefit of collaborative research that deserves evaluation, but can be a difficult criterion to evaluate. The development of personal skills in active-listening, communication, group-process, and coalition-building are at the most basic levels of personal transformation. Moral growth is at a higher level of personal transformation. For researchers, moral growth can be the evolution of values held within a scientific discipline and how those values change through the observation of values held by other scientific disciplines. Or, moral growth can be a shifting social vision that integrates individual freedom and social conscience, and integrates concerns over morality and rights with concerns about care and relationships.[105] All of the different forms of personal transformation need to be self-assessed, as these changes are not likely to be noticed by other collaborators. Once again this evaluation criterion should be evaluated upon completion of a research project, with the most likely evaluation method being interviews.

Social Capital

While the previous conceptual category focuses on changes at the individual level, the creation of social capital focuses on the positive changes that take place in the larger system. While the social capital created from collaborative research will be focused within the scientific community, social capital can spill over to larger society and have significant effects. Interdisciplinary research and the greater understanding of ecosystem response that it provides can influence management of an area. With a greater understanding of the system, ecosystem response to certain management activities can be predicted with greater confidence. With this greater confidence comes enhanced support from the scientific community and the broader community alike. Social capital is also an important mechanism that can work to increase the acceptance of collaborative research designs within the scientific community. Increases in trust among scientists and the creation of information sharing channels are two types of social capital that deserve evaluation.

Forming trusting relationships is one benefit of collaborative research and if those relationships can endure, that is another benefit. But during the formation of these trusting relationships, trust is not just built between individuals, but between scientific disciplines. The ability to recognize and accept the values that underlay specific scientific disciplines plays an important role in the formation of trusting relationships, but also plays an important role in creating trust and respect between disciplines. Researchers who develop these trusting and respectful relationships will end up with a greater appreciation for entire scientific disciplines. This trust and respect can be spilled over to future collaborators and can be shared among colleagues.

Assessing the level of social capital created from a research project can be difficult. While self-reporting techniques may be employed, direct questioning may not be appropriate if social capital is not fully understood. Therefore, more indirect questioning may be the best assessment method. Looking at a researchers 'track-record' of projects they have been involved with may also indicate a certain degree of social capital. Self-assessment questions should be asked before and after a research project so that any changes can be attributed to research design, while investigating an individual's track-record cannot be completed until enough time has passed for future endeavors to be appropriately assessed.

The formation of information-sharing channels is another form of social capital that should be assessed. Collaborative research advocates collaboration between researchers from different disciplines as well as increased collaboration between researchers and managers. Information-sharing channels can be created across both of these boundaries, and both indicate increases in social capital. Some examples of information-sharing channels as social capital likely to be found in collaborative research projects include: increased dialogue between a research group and managers, increased dialogue between a research group and government agencies, and increased dialogue between government agencies. The creation of data-sharing channels (e.g. web-based databases) can also be a form of an information-sharing channel. If these information-sharing channels can be maintained, the increased communication can have a profound affect on the management of a system and on the design of future research and monitoring programs. Assessment of information sharing channels can be conducted by examining journals, reports, web-sites, newsletters, meetings, conferences or any other public outreach portals. This type of information can also be requested directly from all involved institutions and agencies.

Assessment of this evaluation criterion should be conducted in several stages. Baseline assessment should be conducted to determine which information-sharing channels were in existence at the beginning of the project. Assessment upon completion of a project would determine which channels were direct results of the collaborative research design. Future assessments could provide evidence on the fate of these channels and how they have evolved over time.

Collaborative Research Model

Introduction

This collaborative research model was developed to increase the likelihood of successful collaboration on interdisciplinary research and monitoring designs. Because recommendations have been taken from an interdisciplinary research team studying the effects of dam decommissioning and removal, the model is developed for this specific purpose; although, with slight modifications this collaborative research model could be used to help in designing and conducting interdisciplinary approaches to research and monitoring on any sort of river restoration project.

The collaborative research model presented in this section is guided by the typical research model found in the numerous textbooks in classrooms across the United States. This generic scientific research model is typically a circular model, where research objectives are identified, hypotheses are developed, appropriate methodologies are chosen, data is collected and analyzed, and conclusions are drawn. Those conclusions are then used to develop new hypotheses, and the cycle repeats itself. Unfortunately the generic research model is insufficient to be of use to professional scientists investigating something as complex as total ecosystem response to numerous different management activities. The generic research model also does not differentiate between traditional research and monitoring, both of which are necessary in understanding the complexities of total ecosystem response and both of which are required of real-life scientists. A conceptual model for conducting real-life interdisciplinary research and monitoring has been developed (Figure 3). It is important to note that there are two feedbacks within the conceptual model presented in Figure 3, one for traditional research and another for interdisciplinary research.

This model also distinguishes two specific pathways, one for research and one for monitoring. Although separation of research and monitoring in the model is brief, it is important that they be divided as research and monitoring data are collected for different purposes, with different methods, and are used in different contexts. The key distinctions between research and monitoring have been summarized in Table 1.

Table 1. Distinction between Research and Monitoring

	RESEARCH	MONITORING
Objectives	Driven by fundamental science questions	Driven by manager needs
Methods	Standardized methods found in published materials; dependent upon state of the science	Standard methods developed and used by managing agencies
Understandings	Fundamental components and processes (reductionist)	Important change in indicators (biota, ecosystem attributes)
Data Use	Advance the state of knowledge of a particular area, system or process; Typically published	Used to improve management decision-making; Typically **not** published

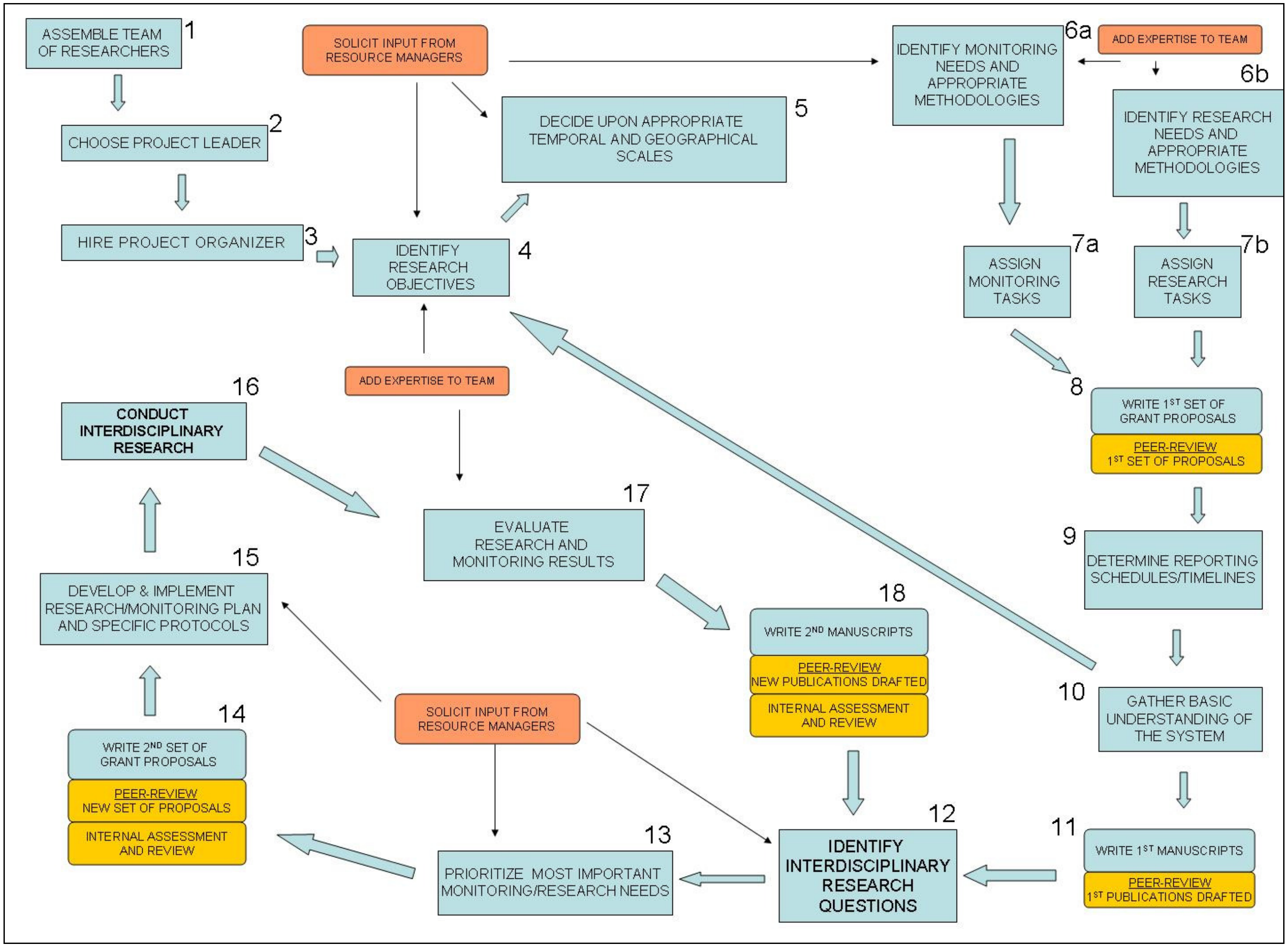

Figure 3. Conceptual model used in the development of a collaborative research model
Yellow boxes indicate assessment steps, red boxes indicate where outside input should be included.

STEP	Table 2. Specific Examples of the Interdisciplinary Research Process from the Fossil Creek Ecosystem Studies Group at NAU. [TABLE TO ACCOMPANY FIGURE 2]					
1. Assemble Team	**Recreational Resources Specialist**	**Aquatic Ecologist**	**Geochemist** (added after step 5)	**Geomorphologist** (added after step 13)	**Civil Engineer**	**Hydrogeologist**
4. Identify Research Objectives	Document user impacts on riparian zones	Determine: 1. Fish populations (native/exotic) 2. Food base 3. habitat distribution	Determine travertine precipitation rates and distribution	1. Watershed characterization 2. Longitudinal and cross-sectional profiles 3. Sediment transport and distribution		1. Spring and baseflow characterization 2. Regional hydrogeologic setting 3. Stressors on the system
			Dam and Pool Distribution			
5. Temporal Geographical Scales		1. Reach scale (200 – 300 meters in length) and cross-sections representing the range of stream characteristics [not all reach sites used by all researchers] 2. Longitudinal profile for entire reach				
6. Methods	Standardized Methods According to Each Discipline	Standardized Methods According to Each Discipline	Standardized Methods According to Each Discipline	Standardized Methods According to Each Discipline	Standardized Methods According to Each Discipline	Standardized Methods According to Each Discipline
8. 1st Set of Grant Proposals	First Year of Multi-Year Proposal to Nina Mason Pulliam Charitable Trust Goals Include: 1. Strengthen the collaborations needed for the long-term success					

	2. Continue data collection and analysis following restoration activities 3. Disseminate lessons learned through the restoration process 4. Establish Fossil Creek as a national case study for dam decommissioning and river restoration.					
9. Reporting timelines	Annual funding reporting requirements; Fossil Creek newsletter; Public workshops					
11. Write First Manuscripts	Jedra and Lee, 2007. *Environmental Management* (in review)	Marks, 2007. *Scientific American* 296 (3) pp. 66-71	Marks et al., 2006. *Geomorphology* (77) pp. 299-307 ~12 graduate and undergraduate theses			
12. Interdisciplinary Research Questions	Recreational Impacts on Stream Morphology and Aquatic Species Distribution (e.g. kayaking impacts on stream morphology)					
		Impacts of Flow Restoration on Stream Morphology and the Influences of Habitat Distribution				
14. 2nd set of Grant Proposals	Joint USFS/NAU Collaborative Management Proposal					
		Marks et al., 2007 Environment and Ecology NSF proposals				
15. Conduct Interdisciplinary Research	Currently Happening (August 2007)					
18. Internal Assessment and Review	Standardized Evaluation with 3 Categories: Outcome Quality; Relationship Quality; Social Capital					

Methodology

The previous five sections of this chapter have provided the background information necessary to understand the development of the collaborative research model presented in this section. This model is the culmination of an extensive literature review combined with lessons learned from members of an interdisciplinary research team. From the literature review on interdisciplinary research, common barriers to interdisciplinary research and likely causes of these barriers have been identified. To solicit recommendations for overcoming the barriers to interdisciplinary research, the more extensive and more developed foundations of other collaborative processes, particularly the use of collaboration in resolving conflict and the use of collaboration in management, have been used. Recommendations for overcoming the barriers to interdisciplinary research have also been solicited from a group of researchers from Northern Arizona University who took an interdisciplinary approach to the design of their research and monitoring program accompanying the dam decommissioning at Fossil Creek, AZ. Open-ended interviews with these researchers provided tremendous insight into additional barriers to interdisciplinary research that have been either down-played or not identified in either the interdisciplinary research or the collaborative processes literature.

Model Presentation

The model assumes that very few, if any, of the participants of collaborative research are familiar with interdisciplinary approaches to research and monitoring, or with any other collaborative process. If collaborative research is to be successful, all members of an interdisciplinary research team must know what to expect from a collaborative process, and what can be expected of them. The background information provided in the previous sections of this chapter was designed to help collaborative research participants become more informed on collaborative research. Sufficient information has been provided for researchers to recognize the value of both interdisciplinary research and collaborative processes, thus increasing the likelihood of successful collaboration.

This model is presented in chronological order, from project conceptualization to project evaluation upon completion. To give a collaborative research project the best chance at success, it is recommended that all of the numerous tasks suggested in this model be completed. That being said, it is realized that there are certain budgetary and time restrictions that are linked to real-life research projects, thus it may not be realistic for all recommendations to be incorporated into a research design. If this is the case, this model may serve its most useful purpose as a guide to help in resolving problems as they arise. While many recommendations are aimed at preventing the barriers of collaborative research from becoming a problem, many recommendations are included for overcoming barriers once they have presented themselves.

Specific sections are devoted to identifying specific roles that should be fulfilled. Within these sections specific tasks are recommended to the individuals who fulfill those roles. Fulfilling each specific role and incorporating each specific recommendation into the design of a research project may not be necessary for each individual collaborative research project. Depending upon the size, scope and focus of each research project, certain roles and recommendations may not be pertinent to the research design. If interdisciplinary approaches to research and monitoring have already been implemented, this model can also serve as a guide to resolving unexpected problems that arise after a research project has been implemented.

Formation of a Collaborative Research Team

The first step in conducting any collaborative research project is assembling the members (see Figure 2). Participants of a collaborative research team should all be voluntary, as voluntary participants are more likely to approach this new situation with an open mind and a greater willingness to collaborate. The size and the scope of a research project will depend largely on who the team members are. For research on dam decommissioning and removal scenarios, team members can be chosen from a wide array of scientific disciplines. Potential members include: hydrologists, hydrogeologists, biologists, geochemists, ecologists, soil scientists, geomorphologists, engineers, botanists, and social scientists. Each member of the group will bring a unique viewpoint and will allow for a larger set of research questions to be addressed. More members of a collaborative research team means more opportunities for interdisciplinary research, but there are certain tradeoffs that come with having a large research team. With a larger research team securing funding for collaborative research may prove more difficult. Large research groups also increase the likelihood that conflict will arise. Choosing an appropriate size for a collaborative research team comes with certain tradeoffs and is something that deserves careful consideration.

Once all collaborative research members have been assembled, funding must be secured. Funding can be approached in two ways. The more common way has been to fund all team members with one large grant. The second method has been to fund the collaborative research team through individually secured grants. One important lesson learned from the Fossil Creek Ecosystem Studies Group at NAU is that interdisciplinary research cannot be conducted without first obtaining an understanding of the system in disciplinary terms. It is only after an understanding of the system in disciplinary terms has been achieved that interdisciplinary questions can be addressed.

Achieving a disciplinary understanding of the system can require significant time and money. Members of the Fossil Creek Ecosystem Studies Group at NAU have suggested that between 1 and 3 years of disciplinary science may be required before interdisciplinary research can be conducted. Thus, securing large sum and long-term grants is preferable for the first 1 to 3 years of a collaborative research project. This way, monies can be divided proportionately among participants to ensure proper understandings of the system components are achieved. After this initial understanding is achieved, specific interdisciplinary research questions will arise. Individual grants can be secured to support specific collaborations between individual researchers. If large grants are secured to fund many interdisciplinary pursuits, problems may arise when appropriating that money. To help researchers in obtaining both large and individual grants, it has been recommended that an individual should be hired to help in securing funding. One member of the interdisciplinary research team, perhaps the team leader, may need to apply for a small grant to secure funding for this individual. Team collaboration with agency managers can help to identify additional sources of funding. Funding networks such as the National Cooperative Ecosystem Studies Unit can provide funding information, if not direct funding.

ROLE OF A FUNDING COORDINATOR

A funding coordinator is a very specific role within a collaborative research team. The primary task of a funding coordinator would be to help researchers obtain grants to fund interdisciplinary research. A funding coordinator should be someone who is familiar with the types of funding available to interdisciplinary research and is familiar with obtaining this type of funding. This individual should help researchers not only in finding appropriate funding, but should help in obtaining that funding. The funding coordinator can be anyone who is familiar with funding interdisciplinary research, but most likely will be somebody outside the group who is contracted by the collaborative research team. Having a funding coordinator will allow researchers to remain focused on their research and will ease the burden of securing funding for collaborative research.

After a Collaborative Research Team Has Been Formed

Once a collaborative research team has been assembled and funding has been secured, research can begin. For the first 1-3 years, researchers will most likely work individually, drawing upon their own disciplinary experience to achieve a basic understanding of the system. During the first 1-3 years, many important tasks can be completed to ensure that collaborative research is successful. The first task is to get all team members familiar with what they should expect, what is expected of them, and excited about a collaborative approach to research and monitoring. Understanding the full suite of benefits that can arise simply out of participating in a collaborative process will help to motivate researchers. Realizing that these benefits exist can increase the likelihood that they will be realized by a collaborative research team. Researchers who join a collaborative research team are likely to have some knowledge of the benefits of interdisciplinary research, although disseminating this information can be helpful.

Unlike the benefits, the barriers to interdisciplinary research are less likely to be understood by collaborative research participants. To ensure that all team members understand the barriers to interdisciplinary research, it is recommended that adequate background information be provided to researchers. Synthesizing all pertinent information on collaborative efforts into one single document would save valuable time for researchers, allowing them to remain focused on their research. Information on the benefits and barriers to interdisciplinary research, as well as the foundations and benefits of other collaborative processes presented earlier in this chapter provides a good starting point for a project-specific document that can be provided to collaborative research participants.

Another effective method of disseminating pertinent background information would be through more traditional classroom learning (e.g. retreat or workshop). A few hours spent disseminating pertinent background knowledge would ensure that all researchers understand what is expected of them, and what can be expected from the collaborative research process. Classroom style teaching could also help to unite the group of researchers and solidify bonds within the group, as "acknowledging what each side does not know may help to promote the individual honesty and humility necessary for all team members to work together."[106]

Developing trusting and respectful relationships between researchers is essential for collaboration to be successful. This is another task that should be completed during the initial 1-3 years of a research project, while researchers are gathering a basic understanding of the system. Fossil Creek team members suggested that having regular and meaningful contact between researchers is the most effective method in which trust between researchers is developed. To ensure that trusting and respectful relationships are created, regular meetings should be conducted throughout the life of a research program. Regular meetings have been essential in developing trust between researchers of the Fossil Creek Ecosystems Studies Group at NAU. Creating newsletters, writing reports, sharing resources both human and financial, conducting open-houses where research ideas and results are shared with the public, and joint data collection have all been cited as ways in which trust has been developed between researchers.

Another task that should be initiated during the first 1-3 years of a collaborative research project is the creation of common research objectives (Figure 2), although it should be realized that some disciplinary understandings are needed before interdisciplinary questions can be framed. These research objectives should be created by all members of a collaborative research team. It is important that a common temporal and spatial scale be identified for interdisciplinary research questions.[107] Interdisciplinary research literature suggests that simply translating research objectives from a single scientific discipline to the collective group poses many difficulties stemming from the different values underlying scientific disciplines.[108] Developing research objectives in unison may be difficult, but many benefits can arise out of the process. Common research objectives help to get all collaborative research members thinking along the same lines. The process of creating common research objectives can also help to develop trust within the group, and to reveal certain values held by team members. Understanding these values may assist in preventing personality differences from distracting from collaborative research. If research results are to be used to inform management decisions, then managers should be included in the creation of research objectives.

It has been suggested that the biggest obstacle to collaborative research lays in the differences of values held by individual researchers. Largely these differences can be boiled down to the epistemological and ontological commitments that researchers hold about scientific research and the natural world. Preventing these differences from distracting from collaborative research requires acknowledgment of the differing values held by researchers. Providing researchers with sufficient background information on the causes of disciplinary differences can help in acknowledging different values and can help researchers to maintain an open mind. Teaching researchers about the likely sources of value-laden conflict and how conflict can be avoided is another effective way in which these differences can be prevented.

Another source of conflict can arise from personality differences. At Fossil Creek, these personality differences have proven detrimental to the functioning of the interdisciplinary research team. These personality differences are a real-life obstacle that arises when dealing with real-life people, and have been reported by several members of the interdisciplinary research team. While it may not be reasonable to expect personality differences to be resolved, many tasks can be completed to ensure personality differences do not distract from the quality of research that is conducted. The creation of guidelines at the beginning of a project is one method used to prevent personality differences in conflict resolution. Guidelines can identify what language is appropriate, identify appropriate ways to phrase and present positions, ensure all members are treated respectfully, and ensure all members' ideas receive equal attention. Agreeing to guidelines at the beginning of a project will help to avoid strife later in the project.

Creating common research objectives is another task that can help to minimize personality differences. With all researchers supportive of research objectives, researchers are less likely to be perceived as using the group to promote personal agendas.

If disciplinary or personality differences do arise there are several things that research groups can do to mend these differences. One good recommendation comes from a paper titled "Employing Philosophical Dialogue in Collaborative Science."[109] The authors suggest using philosophical dialogue to find the philosophical roots of the personality difference; the differing values. From this dialogue, the realization of similar values will emerge. These similar values can be used as a starting point to finding commonalities, building trust and mending relationships. Guidelines need not be created in the beginning of a collaborative research project. If disciplinary or personal differences begin to distract from the quality of research, guidelines can be created in the middle of the project. If these differences cannot be mended by employing philosophical dialogue and working from commonalities or through the creation of guidelines, replacing team members may be a last ditch effort to ensure that good interdisciplinary research occurs.

THE INITIAL ROLE OF A TEAM LEADER

Once the collaborative research team has formed, a team leader needs to be chosen (Figure 2). The team leader should be a well-respected member of the group and should be somebody who is knowledgeable about both interdisciplinary research and collaborative processes. The purpose of a team leader is to ensure that researchers remain focused on collaborative, interdisciplinary research. As mentioned before, the first task of a team leader is to get all researchers on the same page and excited about collaborative research. This requires the dissemination of pertinent background information on interdisciplinary research and other collaborative processes. If background information is to be provided to collaborative research participants, it should be disseminated by the team leader.

The second task of a team leader should be to help in the creation of any guidelines. Guidelines that identify the type of language that is considered appropriate and the most appropriate ways of framing arguments can help prevent personality differences from distracting from the quality of research conducted. It should be the job of a team leader to enforce those guidelines. If guidelines are continually disregarded, it may be necessary for a team leader to have the authority to remove members of the research team, when that removal is supported by other team members. Another important role of any team leader should be to aid in the creation of trusting and respectful relationships. An expert in mediated negotiation, Barbara Grey describes a long list of tasks that must be performed "to assist in collaborative problem-solving processes, including disparate tasks such as establishing ground rules, managing data, creating a safe climate, and displaying empathy."[110]

Perhaps the most important task of a team leader is keeping researchers focused on interdisciplinary research. It has been suggested that the biggest obstacle to interdisciplinary research is a lack of motivation. Collaborative research can be hard. Researchers must wade through complex literature and familiarize themselves with a strange new language. Reverting to old disciplinary habits can be a lot easier than learning and incorporating the habits of numerous other scientific disciplines. The most important task of a team leader is to provide the motivation for collaborative research and prevent researchers from reverting into disciplinary ruts.

THE ROLE OF AN ORGANIZER

The third and final role recommended in this collaborative research model is that of an organizer. The various tasks of an organizer include: organizing meetings, organizing and writing reports, keeping researchers informed about deadlines, maintaining public outreach portals, maintaining dialogue with managers and funding agencies, as well as maintaining open dialogue within the group. These are the sometimes tedious tasks that are essential for collaboration to be successful, but are the tasks that busy researchers can easily forget about. Contracting somebody from outside the group to fulfill this role would ensure that these tasks are completed, while allowing researchers to remain focused on their research.

While the duties of an organizer will vary with each individual research project, the role of an organizer is most important at the onset of the project. Even for small research groups, it has been suggested that a minimum of 20 hours per week be allotted for an organizer at the beginning of a project. Depending on the project, those hours can be cut down as the project nears completion.

The organizer hired by the Fossil Creek Ecosystem Studies Group at NAU has provided many insightful recommendations for anyone fulfilling this role. Feeling that the amount of collaboration that took place "could have been more," when asked what she would do differently if she could start over again, she responded that she "would be more involved at the beginning about getting the most from collaboration." She also advocates that researchers "need an open mind set" and that there is a "need to set up guidelines in the beginning." When asked for any advice she would give to anybody fulfilling an organizer role, she responded that you "can't lose heart - if researchers do not respond to your requests, find other ways to obtain the information you need." She also highlighted the importance of keeping pressure on researchers to ensure that deadlines are met. The most important piece of advice that she could offer to an organizer was to "think on your own" and not be afraid to "input you own ideas."

Conducting Interdisciplinary Research

As a basic understanding of the system in disciplinary terms is being achieved, interdisciplinary research can develop (Figure 2). First, interdisciplinary questions must be identified. While researchers are conducting their initial 1-3 years of disciplinary research, obvious interdisciplinary questions will arise. The collaborative research team must collectively prioritize these interdisciplinary research questions, paying special attention to the most relevant research questions, and questions which can realistically be answered. Managers can be helpful in identifying research questions that address management objectives and should be included in deciding which research and monitoring questions are pursued. Identifying certain researchers who will work on specific questions is another important part of deciding which interdisciplinary questions should be pursued. It is not realistic for all researchers to be involved in answering all research questions. Ensuring that all researchers are assigned an appropriate workload deserves special attention. Once appropriate interdisciplinary questions have been determined and team members have decided which question they will work on, the difficult task of conducting interdisciplinary research will begin.

First, team members must familiarize themselves with the scientific disciplines of their collaborators. This requires understanding the epistemological and ontological commitments required by that discipline, working through pertinent background literature on the topic, and familiarizing with any specialized vocabulary. These tasks can require significant time and effort. It is very important that researchers remain motivated through this process. Although this learning should be largely individual, researchers should utilize their collaborators expertise. Collaborators can answer questions, provide recommendations for pertinent background material, and be a source of background information themselves. Experienced team leaders and organizers can also aid in synthesizing relevant background information. If collaborators are unwilling or unable to provide this assistance, a mentor may be able to provide these services.

It is extremely important that an open dialogue be maintained between collaborators while researchers are familiarizing themselves with other disciplines. During this time, understandings of the system should be shared, hypotheses should be discussed, and research methodologies should be debated. At all times, researchers should be thinking about how their specific disciplinary understandings fit into the big picture. Understandings of the complex system being studied will likely change over time as other disciplinary understandings are slowly incorporated into the big picture. These understandings need to be discussed among collaborators to ensure all researchers share a common understanding of the system.

From this common understanding, hypotheses can be developed. Once hypotheses are identified, research methodology can be developed. Because different disciplines have vastly different ideas of acceptable methodologies for inquiry and explanatory models, it may be easier for researchers to maintain allegiance to known research methods, explanatory models, and techniques of statistical inference than it is to investigate new ones. If this occurs, the most appropriate research methods may be ignored and hostilities may arise. Researchers must keep an open mind and investigate all options before deciding upon the most suitable methods of conducting research. A lack of motivation is the biggest obstacle to finding the most appropriate research design.

To identify the most appropriate research methods and explanatory models, several techniques have been suggested. First, transferring research methods acceptable to one discipline to the bigger picture can be an effective way in which relevant research methods are identified. Using analogies can help to justify the use of certain methods to other researchers. Just as research methods can be transferred from specific disciplines to the big picture, so can explanatory models be transferred. As many research methods and explanatory models as possible should be transferred from specific disciplines to the bigger picture to ensure that appropriate methods and models are not overlooked. Also, with many methods and models applied to the big picture, new and better methods and models can be developed. Realizing the strengths of specific models and research methods, and combining them with the strengths of other models and research methods can pave the way for the creation of a new, more appropriate research methodology or explanatory model.

While interdisciplinary research is being conducted, researchers should always be thinking toward the future and always approach their understandings of the big picture critically. Understandings of how all disciplinary knowledge fits together may not always be correct the first time. Researchers should always be thinking of different ways in which their disciplinary knowledge can fit into the big picture as well as new, interdisciplinary questions that can help to further the understanding of the system being studied and appropriate methodologies for achieving that better understanding. As understandings of the system being studied change, management objectives will also change. Changing management objectives should be relayed to researchers so that new research designs can be created or old research designs can be modified appropriately.

THE ON-GOING ROLE OF A TEAM LEADER

While a team leader's importance is greatest at the beginning of a collaborative research effort, a team leader has many important jobs while interdisciplinary research is being conducted. Because interdisciplinary research often requires more time and effort than reductionist approaches, it will be easy for researchers to slip back into disciplinary ruts. This is especially true when collaborators are trying to develop their interdisciplinary research designs. A team leader should play an active role in developing research designs to ensure that appropriate research methods are employed and appropriate explanatory models are used.

Team leaders can also teach researchers how to temper their viewpoint to include the understandings of other scientific disciplines. This is an essential task for successful collaborative research, but may be an unfamiliar one for researchers. As most team leaders will have already experienced collaborative research, the team leader can provide strategies for incorporating other disciplinary knowledge as well as examples of what other similar collaborative programs have done. Teaching researchers to temper their viewpoints and understandings will increase the likelihood that they realize the full suite of potential benefits of collaborative research.

Upon Completion of a Collaborative Research Project

The previous section of this chapter has highlighted the importance of evaluating collaborative research projects. It is recommended that one member of the collaborative research group, or the organizer, take on the task of conducting interviews and writing an evaluation of the project upon completion (Figure 2). This should also be thought of as a form of assessment, not just of the quality of data and the understandings inferred from that data, but also of efficiency of the collaborative process and of the project as a whole. While evaluations may help to identify some of the strong and weak points of that particular collaborative research effort, the true benefits of systematic and standardized evaluations will not be realized until enough evaluations have been complied to be used in a rigorous comparative analysis effort. Evaluations conducted by a member of the collaborative research team upon completion of a research project will likely be more thorough than evaluations conducted by an outsider. Evaluators will be more familiar with evaluation criteria and researchers will likely be more honest and open during interviews if the interviewer is someone they trust. The standardized evaluations presented in the previous section can be used to evaluate the collaborative research design.

Table 3. Summary of Collaborative Research Model

TASK	DUTIES	Notes	
Formation of Collaborative Research Team	Assemble Team Members	All members should be voluntary	
	Hire Funding Coordinator	Tasks include:	Identify funding sources
			Help write grant proposals
	Secure Funding	Similar funding for all researchers	
After Team Has Been Formed	Choose a Team Leader	Tasks include:	motivate researchers about collaborative research
			help create common research objective
			help develop trusting relationships
			disseminate background information on interdisciplinary research
			disseminate background information on collaborative processes
			help researchers to realize differing values
	Develop Trusting Relationships		
	Create Common Research Objectives	Involve all researchers	
	Develop Guidelines	Guidelines prevent personality differences	
	Conduct Disciplinary Research	Gather basic understanding the system in disciplinary terms	
	Choose an Organizer	Tasks include:	organize and help write reports
			keep researchers informed on deadlines
			maintain public outreach portals
			help maintain open dialogue between researchers
	Determine Reporting Schedule / Timeline	Timeline applicable for all researchers	
Conducting Interdisciplinary Research	Identify Interdisciplinary Research Questions	Consult resource managers	
	Prioritize Interdisciplinary Questions	Consult resource managers	
	Assign Researchers to Specific Questions	Ensure appropriate workloads	
	Decide Upon Appropriate Methodologies	Can be from borrowed from one discipline, or from many	
	Researchers Familiarize With Other Disciplines	Extensive literature review, familiarize with terminology	
	Maintain Open Dialogue		
	Share Findings With Other Researchers		
	Think About the Big Picture	Continually refine understandings of the entire system	
Completion of Collaborative Research	Evaluate/Assess Collaborative Research Project	Use evaluation criteria presented in Chapter 2	

Chapter III. Streambed Morphology

Introduction

When designing and implementing monitoring programs on dam decommissioning and removal projects with the intent of understanding ecosystem response to these activities, appropriate environmental parameters need to be monitored. Monitoring programs can only be successful if the most relevant management orientated indicators are chosen to be monitored. The use of conceptual models can aid in selecting appropriate indicators to be measured, as conceptual models can help to realize the interconnectedness of ecosystem components and identify the primary pathways between stressors and ecological attributes (Noon, 2003; Gawlik, 2004). A conceptual model for functioning of the Fossil Creek ecosystem was developed in this thesis (Figure 4).

While this conceptual model was developed specifically for Fossil Creek, it is generic enough to describe the functioning of most aquatic systems found in the Western United States. Using a conceptual model such as this one helps to realize the pathways where environmental stressors are likely to show their effects on measurable environmental parameters. At first glance it becomes apparent that streambed and channel morphology are extremely influential in defining nearly all aspects of ecosystem structure and function.

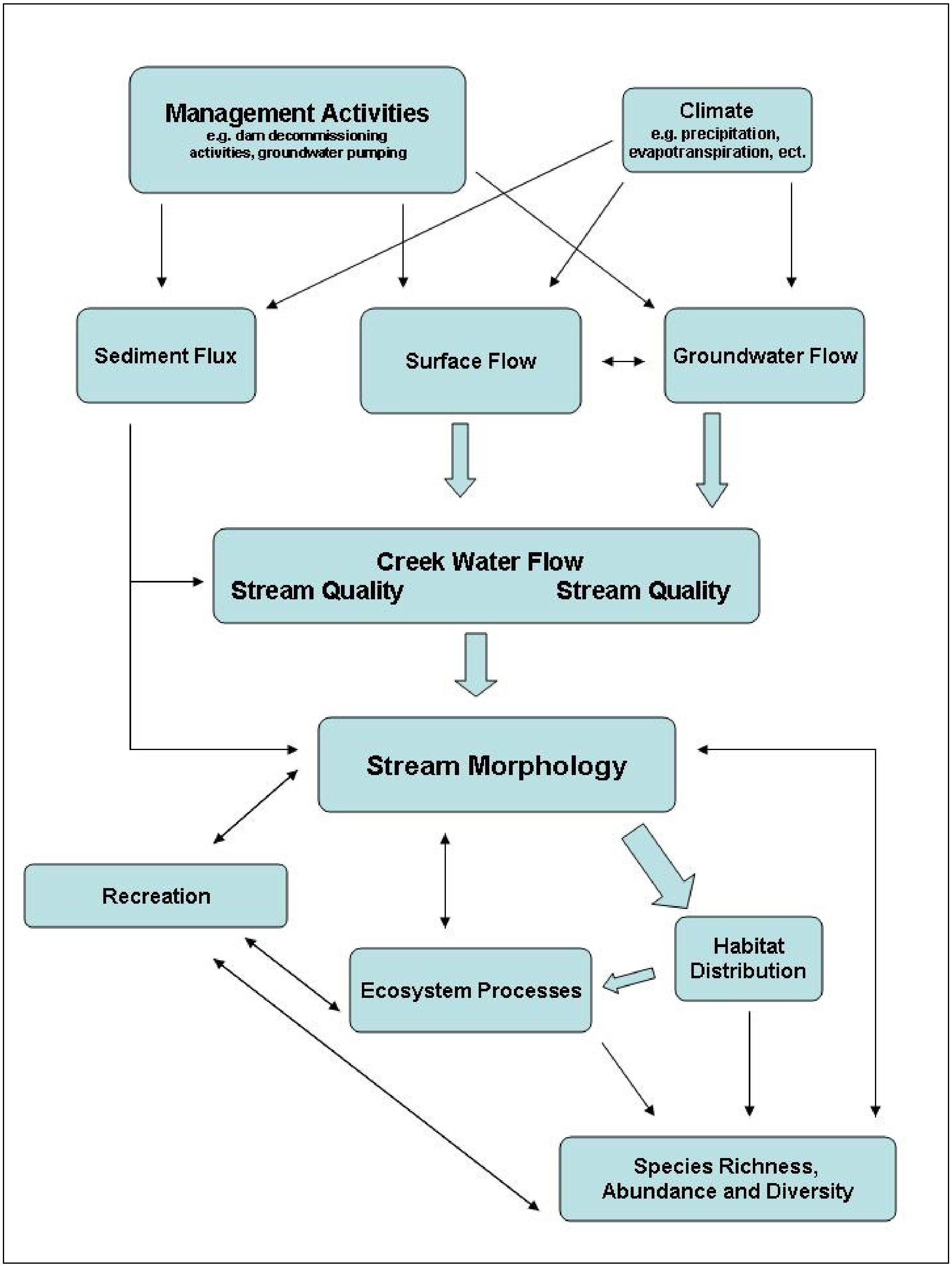

Figure 4. Conceptual model of the functioning of the
Fossil Creek aquatic ecosystem

Because streambed and channel morphology will likely respond to decommissioning activities in obvious ways, and because these changes in morphology will likely drive changes throughout the entire ecosystem (Kellerhals and Church, 1986), a critical monitoring need in programs accompanying dam decommissionings is the need to monitor changes in streambed and channel morphology, including sediment storage.

Understanding streambed and channel morphology response to decommissioning activities is also important for another reason. Characterizing and quantifying streambed morphology can help to characterize the dynamics of particular systems so that meaningful comparisons can be made between systems. From these characterizations, the response of similar systems to similar management activities can be predicted with greater confidence and the risk of further ecosystem degradation can be minimized. Several classification systems based on geomorphology can be found in the literature (see Frissell et al., 1986; Rosgen 1994, 1996).

Linking Geomorphology and Biology

Several direct links between stream morphology and biological populations have been reported in the literature. Murdock and Dodds (2007) investigated the link between benthic algal biomass and stream substratum topography. In their study they conclude that, "Individual substrata and microsubstrata characteristics can have a strong effect on benthic algae development and potentially affect reach scale algal variability as mediated by geomorphology" (Murdock and Dodds, 2007). Sullivan et al. (2006) qualified stream geomorphic condition at 44 reaches in 26 Vermont Rivers and sampled the fish communities at these reaches. The authors reported that "geomorphic condition explained up to 31% of the total variance observed in models for species diversity of fish communities, 44% of the variance in assemblage biomass and 45% of the variance in a regional index of biotic integrity" (Sullivan et al., 2006). From these results, the authors conclude that "geomorphic condition is a dominant factor affecting entire fish communities" (Sullivan et al., 2007). Walters et al. (2007) compared $\delta^{13}C$ of consumers at reaches with two different geomorphic conditions, characterized as either rock-bed or sand-bed. They concluded that reach morphology strongly affects consumer $\delta^{13}C$ and that these affects have important implications for stream food-web studies (Walters et al., 2007). Mussel abundance in southern Appalachian catchments has also been directly related to stream morphology (Gangloff and Feminella, 2007).

The link between streambed and channel morphology and biotic population has been well established (Benke et al., 1988; Death and Winterbourne, 1995; Ligon et al., 1995; Townsend et al., 1997; Norris and Thoms, 1999; Hudson, 2002; Stanley and Doyle, 2002; Rinne and Miller, 2006; Fisher et al., 2007). While certain studies claim to quantify a direct link between stream morphology and stream biota, it has been suggested that indirect links between stream morphology and biological populations may be equally influential, if not more influential, than the direct links. The conceptual model presented in this chapter identifies two basic mechanisms by which stream geomorphology regulates biological populations: habitat distribution and ecosystem processes. The mechanism receiving the most attention by scientists thus far has been habitat distribution, although geomorphic influences on ecosystem processes have recently been receiving more attention.

Perhaps the most prominent concept linking the geomorphology of lotic ecosystems to biological populations has been the idea of an 'ecological' or 'habitat template' (Southwood, 1977; Poff and Ward, 1990; Poff 1997; Fisher et al., 2007). First popularized by Southwood (1977), the concept of habitat template explains the distribution of biota by relating the spatial and temporal heterogeneity of a habitat with the life histories of specific organisms (Fisher et al., 2007). That is, if an aquatic system is characterized by frequent disturbances, the biota of that system will exhibit certain characteristics that help them to flourish under a frequent disturbance regime. The habitat template predicts that similar biota will be found in aquatic systems dominated by the same influences on stream geomorphology. This construct provides a predictive framework for understanding the distribution of stream organisms (Fisher et al., 2007) by qualifying the geomorphic influences on habitat distribution. This well-accepted concept of a habitat template goes a long way to highlight the importance of geomorphic influences on stream biota through the regulation and distribution of habitat.

Supported by the concept of habitat templates, researchers have been quantifying this link between geomorphology, habitat distribution and biological populations. Much of this work has focused on benthic invertebrates. Death and Winterbourne (1995) investigated the relationship between habitat stability and benthic invertebrate richness density and evenness. They found that "Species richness and density were markedly higher at the more stable sites, but species evenness peaked at sites of intermediate stability" (Death and Winterbourne, 1995). Testing the habitat template concept, Townsend et al. (1997) looked at the relationship between the traits of 35 invertebrate taxa and intensity/frequency of disturbance, defined by bed movement during high discharge events. They found that "taxa associated with more disturbed conditions generally displayed a larger number of resistance and resilience traits, combined, than taxa associated with more stable stream beds" (Townsend et al., 1997). With verifiable scientific evidence that seems to validate the concept of habitat templates, it is reasonable to conclude that "[s]tream biotic composition is strongly influenced by physical habitat" (Norris and Thoms, 1999). Physical habitat, consequently, is strongly influenced by geomorphic processes (Fisher et al., 2007). The most important geomorphic processes include surface flows and sediment flux. Altering the flow of sediment and water will alter habitat – "sometimes dramatically, but often subtly – and the ecology of a river can be significantly, and sometimes disastrously, altered" (Ligon et al., 1995).

While the effects of streambed and channel morphology on stream biota are largely due to habitat alteration (Benke et al., 1988; Ligon et al., 1995; Norris and Thoms, 1999), streambed and channel morphology also influence biological populations by regulating important ecosystem processes, at a variety of different scales (Fisher et al., 2007). The ecosystem process that has received the most attention by researchers has been nutrient cycling. Fisher et al. (2007) focused their work on the interface between biogeochemistry and geomorphology. An important realization from this work has been that "nutrient spirals occur along flowpaths with transport vectors of varying angles, dictated by slope and sediment characteristics along complex surface and sub-surface flows…" (Fisher et al., 2007). These flowpaths are not restricted to stream channels but integrate entire landscapes as flowpaths with consequences on nutrient retention and cycling (Fisher et al., 2007).

Other work has focused on direct influences that stream morphology has on nutrient cycling. Alexander et al. (2000) report rapid declines in the rate of nitrogen removal with channel size in the Mississippi River basin. Thoms (2003) reports on the influence of the reduced connectivity of river channels with their floodplains and the consequences that has on dissolved organic carbon. Dahm et al. (1998) write that "redox reactions that cycle various nutrients are patterned in a complex mosaic that is closely linked to the hydrology and fluvial geomorphology of the interface."

Nutrient cycling and availability, in turn, play a determining role in the distribution, abundance and structure of stream biota. While the links established between streambed and channel morphology and biological populations may not be direct, there is strong evidence that validates the claims that stream morphology influences stream biota populations through the regulation of important ecosystem processes.

Several studies have used stream hydraulics to explain variations in biological populations. Because stream hydraulics are intimately related to the geomorphic characteristics of a stream or river, these studies further demonstrate the important role streambed and channel morphology has in determining biological populations. Statzner and Higler (1986) used stream hydraulics to explain variations of benthic macroinvertebrates across latitudes. Newbury and Gaboury (1993) related hydraulics to fish populations and highlighted the importance of hydraulic habitats in fisheries management.

Geomorphic Effects on Aquatic Ecosystems

Stream morphology regulates the distribution of all species, at all trophic levels. Plants require specific conditions to thrive, namely sufficient sunlight, carbon dioxide and nutrients. The morphology of a river directly determines the distribution of water depth and velocity (Kellerhals and Church, 1986), which consequently regulate the delivery of necessary conditions for primary producers to survive. In studies testing the River Continuum Concept, "geomorphic characteristics (e.g. slope and hence hydraulic energy) seemed most important in explaining the variability in primary production…" (Benke et al., 1988). Ecosystem processes, such as nutrient cycling are also important in determining populations of primary producers by providing the nutrients necessary for photosynthetic plants to survive. Concentrations of inorganic nitrogen, a common limiting nutrient for primary producers, are typically higher in the saturated sediments of the hyporheic zone (Fisher et al., 2007). Hydraulic exchanges between surface waters and the nutrient enriched waters of the hyporheic zone are regulated by geomorphic processes (Fisher et al., 2007). Thus, both the physical parameters of an aquatic system and important ecosystem processes are regulated by streambed and channel morphology.

From primary producers, energy and nutrients move among biotic and abiotic components of the system through a number of different processes. Biota control the energy and nutrient flow through an ecosystem by processes that include mineral adsorption by plants, the death of plants and animals, decomposition by microbes, consumption of plants by herbivores and consumption of herbivores by predators (Chapin et al., 2002). All of these processes are directly regulated by populations of these organisms. Populations are in turn regulated by, among other factors, habitat distribution (Benke et al., 1988). "Much of the literature in stream fish ecology suggests that fish production is related directly to the availability of adequate habitat, to production of its food resources, or to both" (Benke et al, 1988). For invertebrate production, "Substratum condition, as defined by many aspects of basin geology, geomorphology, and hydrology, is critical to whether an organism can exist in a particular environment, and determines the upper limit of its standing stock biomass" (Benke et al., 1988). The importance of microbes to energy and nutrient flow through aquatic ecosystems is also firmly established in stream ecology (Benke et al., 1988).

Abiotic processes include ingassing and outgassing, atmospheric deposition, the weathering of rocks, suspended sediment resulting from this erosion, and the dissolution of these materials in water. Affecting water quality, these abiotic processes are largely regulated by water velocity and other channel characteristics, which are consequently determined by streambed and channel morphology (Kellerhals and Church, 1986). Because many studies have linked water quality parameters to presence/absence of macroinvertebrate taxa (Malan and Day, 2003), the effect of a changing streambed and channel morphology becomes apparent. Thus, streambed and channel morphology indirectly regulate both the biotic and abiotic factors which govern biological productivity and nutrient cycling.

Energy is lost from the ecosystem when organic matter is oxidized back into carbon dioxide by the respiration of plants, animals and microbes (Chapin et al., 2002). Just as streambed and channel morphology play an integral role in the distribution of species at lower trophic levels through habitat distribution and regulation of important ecosystem processes, morphology regulates the populations of plants, animals and microbes at the highest trophic levels through the same mechanisms.

The effects of a changing streambed and channel morphology are not limited to natural processes. Morphological changes also impact recreation. As different recreation activities will affect ecosystems in different ways, understanding the effects of dominant recreation activities is an important aspect of any monitoring effort accompanying dam decommissioning projects. While fishing will affect fish populations, the impacts of kayaking will be markedly different. Because certain recreation activities such as kayaking can affect streambed and channel morphology in shallow, low discharge creek systems and because these changes can be felt throughout the entire ecosystem, it is important that the link between recreation activities and streambed and channel morphology be examined.

Importance of Scale

"Indeed, any conceptualization of an ecosystem requires constraining the spatial and temporal scales of analysis. Thus, it is of particular importance to match the ecosystem boundaries to the question being asked or the processes being studied" (Post et al., 2007).

When considering the importance of monitoring the response of streambed and channel morphology to decommissioning activities, the significance of choosing an appropriate scale becomes apparent. Morphology can be monitored at several different scales, ranging from the distribution of micro-habitats to longitudinal studies of entire watersheds. While each scale has its benefits and limitations, no one scale is necessarily more effective than any other. An appropriate scale should be chosen according to the particulars of the system being studied. Research/monitoring objectives, decommissioning activities, dominant influences on morphology, and stream characteristics should all be considered when determining appropriate scales to monitor streambed and channel morphology response to decommissioning activities.

Time scales need to be taken into consideration as well. While intense short-term monitoring during the decommissioning process can provide tremendous insight into ecosystem response, the results from long-term monitoring programs are likely to be markedly different. It is also important to realize that geomorphological characteristics and biological populations will respond at different timescales (Adams et al., 2002; O'Neill, 1999). "Problems arise when trying to link geomorphic and ecological processes that can operate at different, but variable, temporal scales" (Post et al., 2007). Choosing an appropriate time scale will depend on research objectives and the unique influences on each individual system.

"A common conceptualization of ecosystems is crucial for forging stronger links between geomorphology and ecosystem ecology. Because ecosystem processes are scale dependent, the choice of boundaries is of profound importance to our common view of an ecosystem and to the scope and validity of questions being asked within that ecosystem" (Post et al., 2007).

Monitoring Methodologies

Just as choosing a scale for monitoring streambed and channel morphology response to decommissioning activities is dependent upon research/monitoring objectives and stream characteristics, monitoring methodologies are also dependent upon a similar range of criteria. While the range of monitoring methodologies can be narrowed after appropriate temporal and geographic scales have been determined, many different methodologies exist due to the numerous scientific disciplines incorporated in streambed and channel morphology.

An appropriate monitoring methodology can only be chosen after the dominant processes affecting morphology have been determined. For example, if lentic systems transport large amounts of sediment, or if large amounts of sediment are likely to be flushed downstream as a result of decommissioning activities, then monitoring methods appropriate to tracking sediment load and distribution should be employed. If streambed and channel morphology is characterized by high deposition/erosion of chemical precipitate, as in travertine-depositing streams, then perhaps the models and methodologies appropriate for aquatic geochemistry should be utilized. Physical monitoring of topography can be a viable monitoring methodology under a wide range of circumstances because physical surveying of the streambed can track the effects of both sedimentological and geochemical processes on streambed and channel morphology.

Oftentimes effects on stream morphology are not be restricted to one dominant process and therefore a combination of methodologies from a combination of different scientific disciplines may be the most appropriate approach. Appropriate methodologies will likely require the integration of several scientific disciplines. These methodologies should be determined on each individual system, dependent upon the processes at work in that system.

Research Objectives

Problems arise in determining the most appropriate scales and methodologies for monitoring streambed and channel morphology response to dam decommissioning activities. These problems can be attributed to a lack of information on the success of different approaches. Not only have very few dam decommissionings been accompanied by comprehensive ecological studies, but the few studies that have been published have neglected to monitor streambed and channel morphology response. It is the objective of this chapter to evaluate one particular monitoring methodology at one particular scale utilized by an interdisciplinary research team on a dam decommissioning on a travertine-depositing stream at Fossil Creek, AZ. A further description of the interdisciplinary research team and of dam decommissioning activities at Fossil Creek can be found in Chapter 1. Evaluation of this monitoring methodology will be based upon three criteria:

1) Is the method capable of detecting changes that are occurring in the system? Physical monitoring methodologies can only detect changes that occur in a system at a specific resolution. The greater the resolution of survey data, the smaller the change can be detected. For topography, this resolution is largely a function of point density. Evaluating the monitoring methodology used at Fossil Creek will need to consider the point density of survey data, the time elapsed between surveys, and comparison of travertine precipitation rates calculated using this methodology with calculated rates of travertine precipitation using other methodologies.

2) Is it precise and accurate? Physical monitoring methodologies are only useful if they accurately portray actual changes in the streambed, and if the precision of this data is greater than the changes being measured. Survey data are only as accurate and precise as the equipment and methods used to collect that data. Evaluating this criterion will involve comparing the changes detected by the total station survey methodology to the accuracies in collection of survey data. The preciseness of total station survey methodologies will also be evaluated. Backsite checks provide an accurate description of errors associated with gun drift and changes in atmospheric conditions (pers. comm. with J. Hazel, 2007). Differences in backsite checks throughout the survey will be compared to changes detected by the physical surveying methodology to determine the preciseness and accuracy of survey data.

3) Are the monitoring data of value to resource managers? Physical survey data can be used for two purposes: research and monitoring. To evaluate this criterion, the quality of survey data and the information about the system it imparts will be compared with management objectives.

Monitoring Methodology

Due to the high precipitation rates of travertine and the tendency to build large impoundment structures (Malusa, 2003; Schwartz, 2004), it was determined that physical surveying of the streambed at the reach-scale would be the most appropriate monitoring methodology. With reported travertine precipitation rates at Fossil Creek on the order of 10 centimeters per year, or greater (see Malusa et al., 2003; Schwartz, 2004; Marks et al., 2006), it was hypothesized that travertine precipitation rates and patterns are significant enough to be detected by a high density physical surveying methodology. In total, four reaches were surveyed (Figure 5). Reaches ranged from 100 to 200 meters in length and all reaches were located within the initial 6.5 kilometers of perennial flow where travertine precipitation rates are highest (Figure 5). Reaches were chosen to include at least one travertine dam structure and at least one pool. Initial survey data were collected prior to full-flow restoration during spring, 2005. Resurvey data were collected during June, 2007.

Survey Methodology

Survey reaches in the canyon setting of Fossil Creek are characterized by steep slopes, and in places, dense vegetation. These environmental conditions preclude kinematic-GPS techniques due to the loss of satellite lock and position fix during GPS surveying. These conditions also preclude the use remote sensing techniques. Due to the dense riparian vegetation at Fossil Creek, a technique that works under the canopy is required. In order for the resolution of repeat photometry to be a valid technique to monitor travertine precipitation, high camera angles are needed. Again, the dense vegetation at Fossil Creek prohibits these high camera angles, and thus the effectiveness of this method.

As a result, conventional total station surveying provided the best compromise of speed, accuracy, and coverage. A total station is an optical instrument that combines an electronic theodolite with an electronic distance measuring device. The theodolite records angles from a reference point while the electronic measuring device measures the distance to a reflective prism. The electronic distance measuring device utilizes an infrared carrier signal that is emitted from the instrument. As this signal is returned from a reflective prism, the speed-of-light lag between the outbound and return signal is translated into distance by an onboard computer. With the aid of trigonometry, angles and distances are converted into coordinates of actual positions of surveyed points. This conventional survey technique was utilized to collect topographic data of the streambed for terrain analysis. The data acquisition process involved two stages; first benchmarks and backsites were verified on all total station setups while the second stage involved data collection and processing.

Setup Verification

High-density survey information, at resolutions sufficient to fully represent three-dimensional channel form, was collected at 4 reaches along the travertine-precipitating reach of Fossil Creek. Surveying protocol was developed and documented according to standard practices for ground surveying (United States Army Corps of Engineers, 2007).

Previous work in southwestern canyon riparian settings shows horizontal repeatability of +/- 10 cm and vertical repeatability of +/- 20 cm (Hazel et al., 2007). Due to dense vegetation at all resurvey sites, all control points were utilized as benchmarks for total station setups. The control points are stable survey marks monumented by a P-K hardened masonry nail, or a piece of rebar. One control point that was not occupied by a total station was utilized as a backsite. A backsite setup consisted of a Sokkia reflective prism mounted on an optical-plummet equipped tribrach (Seco or Sokkia) attached to a Crain Tri-Max slip-leg, adjustable tripod. The height of both benchmark and backsite targets were recorded to within +/- 1 mm. When benchmark and backsite locations were switched, the tripods were left intact, total stations and prisms were switched, and heights were remeasured and recorded.

The coordinate values for each benchmark and backsite were verified by the surveyor using multiple angles in both direct- and reverse-scope and by multiple distance measurement using GPT-2003 total stations. A Tripod Data Systems (TDS) handheld Ranger with TDS Survey Pro surveying software was used for data collection and storage in the field. Unlike older digital data collectors, collected data are immediately written to internal storage. Even with complete loss of power or software lockup the data are retained.

Field Data Collection

Ground surveys utilized 7.6 m extendable rods mounted with tilting, Sokkia reflective prisms. To minimize target height error, all rods utilized were Crain LR STD-series fiberglass leveling rods of the same height. The rods telescope smoothly through four extensions, have minimal sway when extended, and are waterproof. The rods have internal locking and stop mechanisms to ensure that under- or overextension of the collapsible sections does not occur.

A side shot (a single bearing and distance measurement) was used for ground surveying. Data were collected in a particular and consistent manner for the purpose of creating breaklines to be used during analysis of survey data. Data were collected and coded as water's edge, upstream edge of a travertine dam structure, top of dam structure, and downstream edge of dam structure. Where travertine dam structures were too complex to determine one single top of dam breakline, several top of dam breaklines were coded. After breakline data had been collected at waters edge and on all travertine dam structures, topographic slope survey points were collected. Topographic survey points were collected throughout the entire survey reach at an attempted spacing of approximately one point every square meter. Initial survey data consisted of between 200 and 300 points per reach. Resurvey data consisted of between 600 and 750 points per reach.

GPS Methodology

GPS receivers provide position information by repeated measurements on the travel times of digitally tagged radio signals generated by a constellation of satellites. Comparison of data from four or more satellites provides vector information (angles and distances) for the triangulation of latitude, longitude, and altitude (Hazel et al., 2007). All control points and backsites were located using Trimble 4600LS Internal GPS units. After Crain Tri-Max slip-leg, adjustable tripods had been centered and leveled over control points, GPS units were attached to the tripod. The heights of GPS units were recorded, and GPS units collected data under the 'L1 FastStatic' mode. GPS units remained on and logging data for approximately one hour at each control point.

All data were recorded in the internal memory of the 4600LS unit and later downloaded onto a personal computer. GPS data and the resultant 'wobble' from tracking upwards of 10 satellites at a time were fixed using Trimble Geomantic Office software version 1.62 (Trimble, Sunnyvale, California). Both network adjustments and baseline processing were utilized as quality control/quality assurance measures. The GPS points were exported as an ArcGIS shapefile and directly imported into ArcMap. The projection and the geoid for the GPS points were set by the Trimble Geomantic Office software. 1983 UTM state plane projection, Zone 12 North was chosen as the projection and the geoid selected was Geoid99.

Analysis Methodology

ArcGIS version 9.1 (Environmental Systems Research Institute, Redlands, California) was utilized to analyze all survey data. After the GPS data were imported to ArcMap, survey data were imported. First the survey data were fixed and edited using TDS Survey Link software version 7.5.4 (Tripod Data Systems, Corvallis, Oregon). Survey Link converts the raw survey data to coordinates and allows for data editing. Errors in field recording of proper rod heights were identified and fixed. Codings for each survey point were also checked before data were exported to ArcGIS for analysis. All data were exported as a text file, comma delimited. As the initial survey data were shot in feet, they were all converted to meters in Microsoft Office Excel version 11.0 (Microsoft, Redmond, Washington). From either a Microsoft Excel comma delimited file, or a comma delimited text file, the data were imported into ArcMap. To check the accuracy of the survey data, the control points and backsites were rotated to fit the GPS points already in ArcMap.

After survey data had been imported and rotated to fit GPS points in ArcMap, maps of the streambed were created. Maps were created using a triangulated irregular network, or a TIN. This was done with each survey reach in a different data frame. In each data frame, a boundary layer for the TIN was created. Boundaries were created by creating a new polygon layer and connecting the outermost points of each reach, not including control points. A waterline layer was also created for all reaches. This was accomplished by creating a new polyline layer and connecting all survey points coded EWL and EWR [edge of water left, right]. Where the survey data was coded with breaklines, those lines were created by connecting the appropriate points in a new polyline layer. When TINs were created, under the 3D Analyst toolbar, the boundary layer was used as a 'Hard Clip," waterlines were used as a "Hard Line" and breaklines were used as "Soft Line." From these TINs, a cut/fill analysis was performed. This analysis determines sections of net gain and net loss by volume and area that occurred over the more then two years that passed between surveys. Normalizing changes in volume by changes in area resulted in average changes in elevation to be determined. This average change in elevation is reported on the maps displaying the cut/fill analysis.

Results

Maps of the streambed were created from survey data collected prior to full flow restoration (2005) (Figures 6, 7, 10 and 13), after full flow restoration (2007) (Figures 8, 11 and 14), and with a cut/fill analysis performed (Figures 9, 12 and 15). Figure 5 shows the locations of each reach. As surveys were shot in local coordinates, the elevations reported on these maps are not actual elevations.

The errors associated with total station survey methodologies have been reported by the United States Army Corps of Engineers (USACE) (USACE, 2007). Total vertical angle measurement error has been reported as -0.007 meters and +0.015 meters. While the reported errors of resurvey data and the precision of those data are significantly less then the error reported by the Army Corps of Engineers, unfortunately the errors associated with initial survey data are unknown. Thus, for the purposes of this thesis, the errors associated with surveys of the Fossil Creek streambed have been estimated to be +/- 10 centimeters. That is, any observed changes that are less than 10 centimeters are deemed to be within the range of error and are not valid. Changes over 10 centimeters are greater than the errors associated with total station surveying and are deemed to be indicative of real change in the system. Errors of 5 cm or less for total station surveys in the Grand Canyon have been claimed by more experienced, professional surveyors in reaches significantly bigger than those at Fossil Creek (pers.comm. with J. Hazel, 2007).

The surveys at this scale do show the important features at each reach, including travertine dam structures, pools and bedrock ledges (See Figures 4-13). The scale chosen to monitor changes in these features is appropriate for the topography at each reach.

Reach 1

At reach 1 we only have one map made from the initial survey data. Due to extreme vegetation and loss of one control point, Reach 1 was not resurveyed after full flow restoration. Initial survey data collected 438 total survey points. With a surface area of about 1090 square meters, point density is approximately one point for every 2.5

square meters. GPS located points were all within 8 centimeters of surveyed control points.

Reach 2

At reach 2, also called the sunfish barrier reach, initial survey data were collected at a point density of one point per 4.6 square meters. Resurvey point density data were calculated at one point per every 2.5 square meters.

The general trends at Reach 2 include aggradation of travertine dam structures as well as the area 1-3 meters upstream of dam reaches. In these areas, aggradation of one meter or more can be found. The average aggradation rate for nearly all aggrading portions of Reach 2 is just over 0.5 meters. Also, general patterns of erosion between 10 and 30 centimeters along the narrow reach at the downstream edge of Reach 2 and erosion of ~17 centimeters in the upstream portion of the pool located between the upper and lower dam complexes can be found. The erosion seen in the downstream edge of Reach 2 may be due to a lack of survey points collected in that location during the initial survey in 2005. The larger area of erosion seen in the pool located between the two larger dam complexes does contain a few initial survey data points and is likely indicative of real change occurring at that location.

Backsite checks at Reach 2 revealed a maximum vertical error of 2 cm and a maximum horizontal error of 0.5 cm. Surveyed control points were all within 7 cm of GPS located control points for initial survey data and 5 cm for resurvey data.

Reach 3

Reach 3 initial survey data were collected with a point density of one point for every 3.9 square meters. Resurvey data were collected at a point density of one point for every 0.7 square meters. At reach 3, spatial overlap in survey data did not occur to the same extent as other reaches. While pre-full flow restoration survey data used the waterfall as an upstream boundary for the reach, the resurvey used that waterfall as a midpoint for the surveyed reach. As a result, only approximately 50 meters of the creek bed was surveyed by both the initial survey and the post-full flow restoration survey.

From this overlap in data collection, several trends can be seen. First, the large travertine dam causing the waterfall seems to be evolving. While the main water channel seems to have remained on river left, additional flow seeps over the entire width of the creek. This overflow that does not remain in the main channel seems to be precipitating travertine and enlarging the dam structure. In the main channel over the waterfall, the addition of more water seems to be eroding the main channel, as indicated by net loss seen in the cut/fill analysis. The second trend we see is that the large pool just downstream of the waterfall seems to be eroding at the upstream edge and aggrading at the downstream edge of the pool. The average erosion was calculated at approximately 11 centimeters. This is likely due to the fact that the addition of water falling over the waterfall makes the upstream part of the pool more turbulent and does not allow for sediment to accumulate at the bottom of the upstream part of the pool. Further downstream the turbulence subsides and sediment does accumulate on the bottom of the pool. The third trend we see is that areas of slackwater are aggrading. As indicated by the downstream boundary of the resurvey, the cut/fill analysis shows that the calm, slackwater part of this reach is nearly all aggrading. This is likely due to the increased water allowing for more travertine precipitation. Average travertine aggradation at Reach 3, including dam structures and slackwaters was calculated at 17 centimeters. Maximum aggradation found on a travertine dam complex was over 40 centimeters, although this number could be higher because only a small section of the travertine dam complex was surveyed by both 2005 and 2007 surveys. Another interesting trend we see is that all areas of erosion on river left were greater then 10 centimeters, and thus within our detection limit while almost all areas of erosion on river right and through the center of Reach 3 were less than 10 centimeters.

Maximum horizontal error and vertical error for Reach 3 backsite checks were 0.3 cm and 0.4 cm, respectively. GPS located points were all within 2 cm of surveyed control points for both initial survey and resurveys.

Reach 4

Reach 4 initial survey data were collected with a point density of one point for every 3.1 square meters. Resurvey data for Reach 4 were collected at a point density of one point for every 2.5 square meters. As seen in the other reaches, Reach 4 seems to generally be aggrading throughout the entire reach. Average aggradation of all aggrading portions of Reach 4 was calculated to be 18 centimeters. The maximum observed change on travertine dam complexes rarely exceeds 30 centimeters. While there are several pockets where the streambed seems to be eroding, most of these changes are below a total erosion of 10 centimeters. After performing a cut/fill analysis for Reach 4 and setting the error at 10 centimeters, we can see only two distinct areas where total erosion is greater than 10 centimeters. Both of these areas correspond to the downstream most edge of the two travertine dam sections and continue 1-3 meters downstream. Because the travertine dam sections and the few meters upstream of these dams are generally characterized by travertine aggradation greater than 10 centimeters, erosion downstream of these reaches is likely due to increasing turbulence as water continues to drop from higher and higher elevations. This increase in turbulence can perhaps prevent the colonization of algae and travertine deposition, or cause erosion of fragile travertine. Reach 4's proximity to a heavily trafficked dirt road may be another factor that influences the results of survey data. As vehicles travel along County Road 708, a noticeable amount of dust is kick up into the air and is carried from the road down to Reach 4. As Reach 2 and 3 are characterized by at least some erosion greater then 10 centimeters in its deep pools, this may be negated by the influx of dust from the nearby road at Reach 4. Perhaps the turbulence just below the travertine dam reaches at Reach 4 is significant enough to prevent this dust from settling in the pools downstream of the dam complexes.

Maximum horizontal error and vertical error for Reach 4 backsite checks were 1.3 cm and 0.4 cm, respectively. Unfortunately control points could not be located with GPS due to extreme overhead vegetation thus precision of GPS located and survey control points could not be determined.

Conclusion

From the analysis of survey data, we can see several trends in streambed response to full flow restoration. The first trend we see is that travertine precipitation rates are highest closest to the springs, and decline downstream. This is evident in the maximum aggradation seen in each reach, and is consistent with geochemical data collected over the past decade (see Malusa et al., 2003; Germanson, 2006). The maximum aggradation in all reaches is greater than the detection limit of +/- 10cm. In all reaches, the greatest travertine aggradation was found on the tops of travertine dam complexes.

Another trend we see is that essentially all travertine dam structures and the 1-3 meters upstream of travertine complexes are aggrading. Where pools occur between travertine dam complexes, the upstream portions of those pools generally show significant erosion of 10 cm or more. Also, where areas of slackwater have been identified, these are typically characterized by travertine precipitation, although at a rate much slower than travertine precipitation on dam complexes.

Table 4. Maximum and Average Aggradation for the 3 Reaches Surveyed in 2007

	Maximum aggradation	**Average aggradation**
Reach 2	1 m	50 cm
Reach 3	0.5 m	17 cm
Reach 4	0.3 m	18 cm

Table 5. Precision and Accuracy of Total Station Methodology.
Precision in maximum horizontal and vertical error only reported for 2007 survey data.
Accuracy reported for 2005 and 2007 survey data, respectively.

	Max. Horizontal Error	Max. Vertical Error	Accuracy with GPS located points
Reach 1	n/a	n/a	8 cm
Reach 2	0.5 cm	2.0 cm	7 cm, 5 cm
Reach 3	0.3 cm	0.4 cm	2 cm
Reach 4	1.3 cm	0.4 cm	n/a

Fossil Creek, AZ

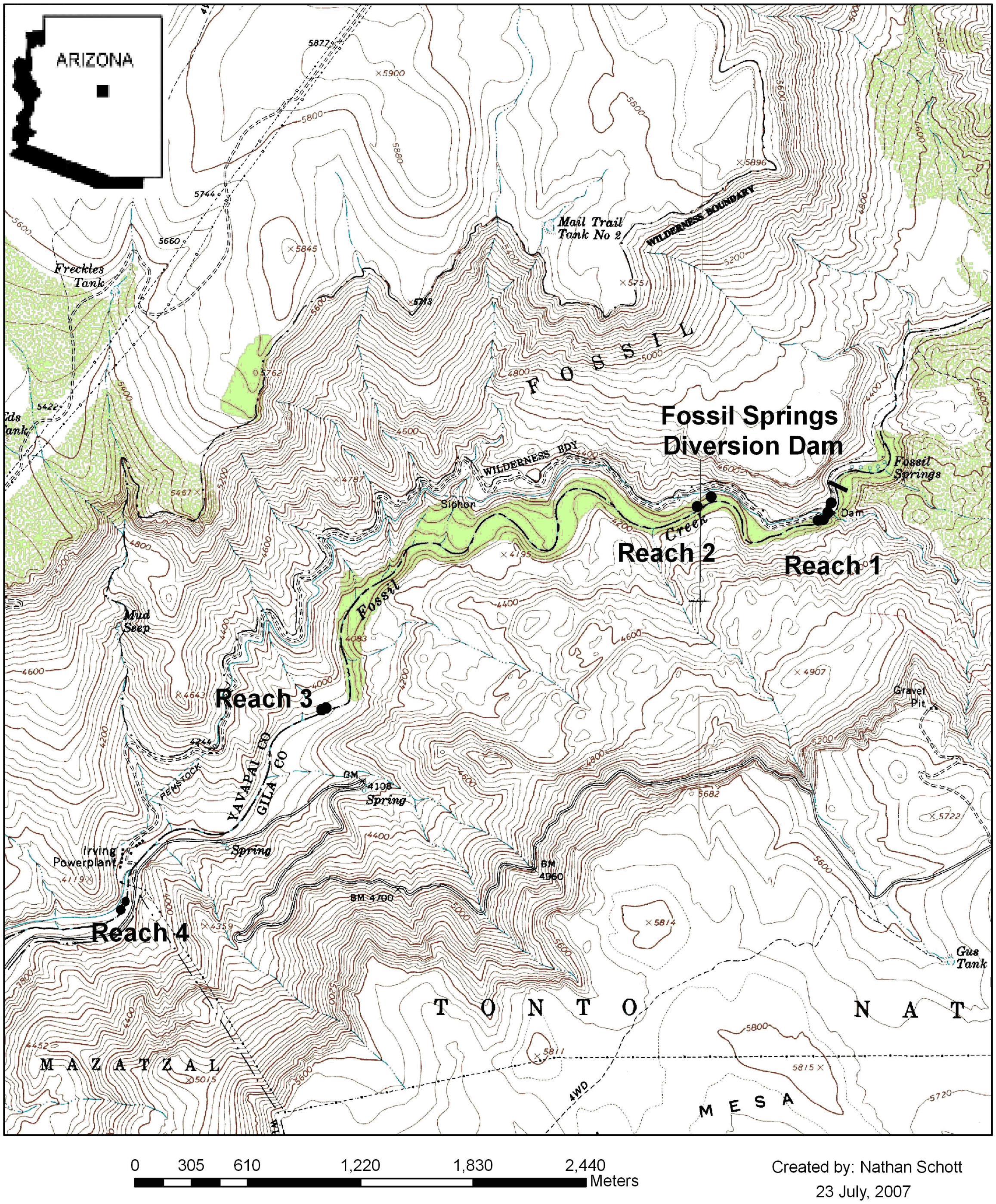

Figure 5. Map of Fossil Creek, AZ with the 4 survey reaches labeled.
Dots indicate GPS located control points from this study.

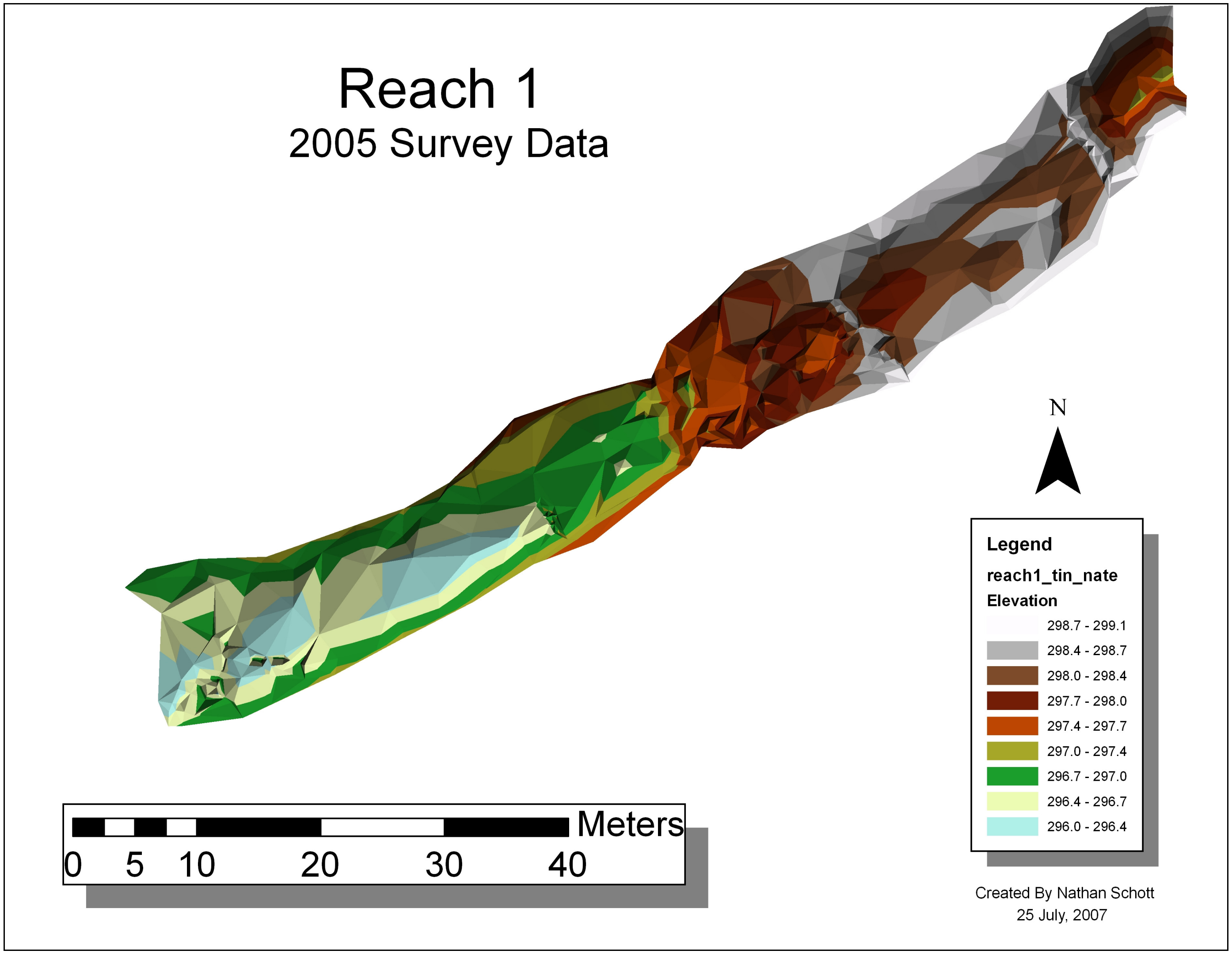

Figure 6. TIN of Reach 1, 2005 Survey Data

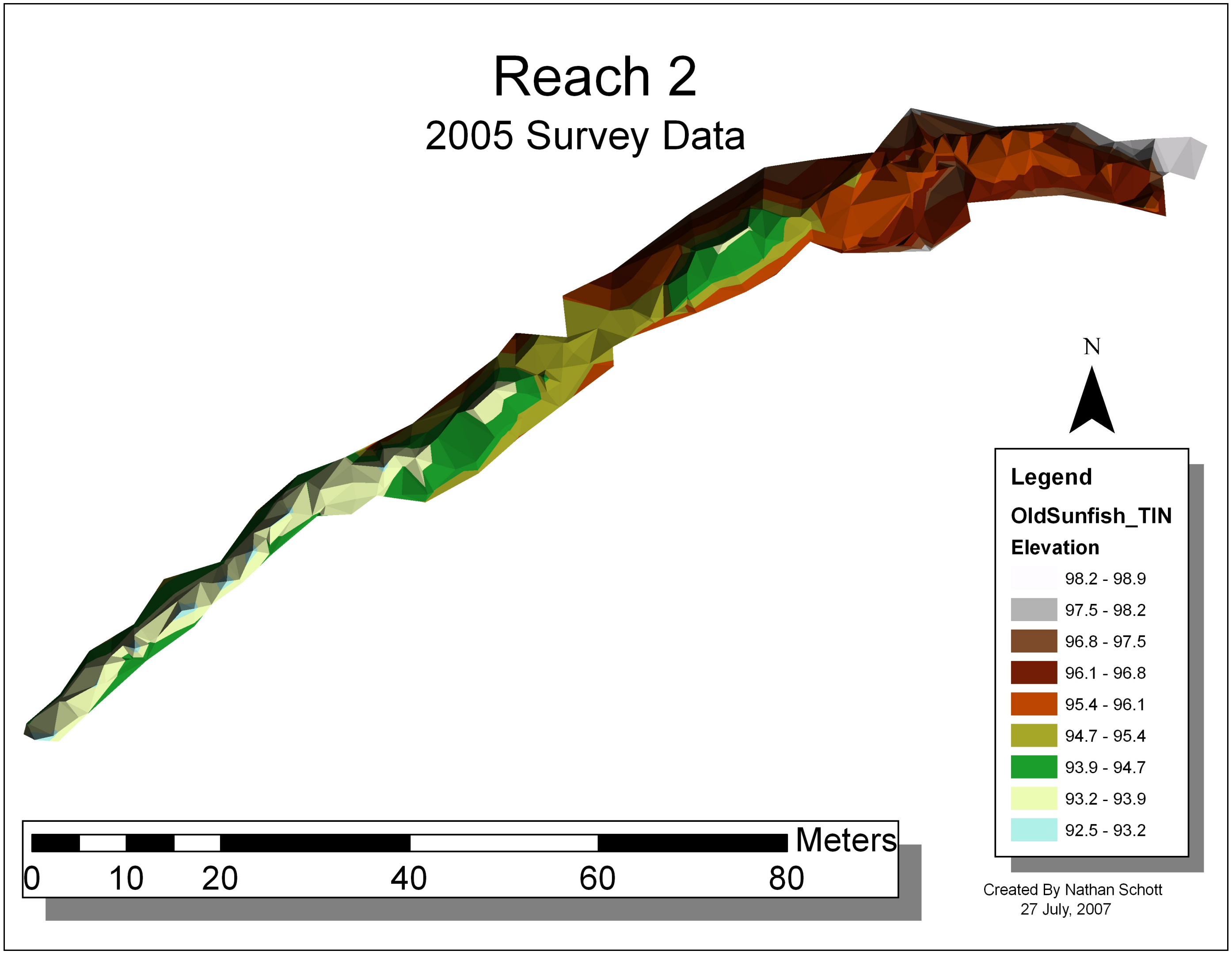

Figure 7. TIN of Reach 2, 2005 Survey Data

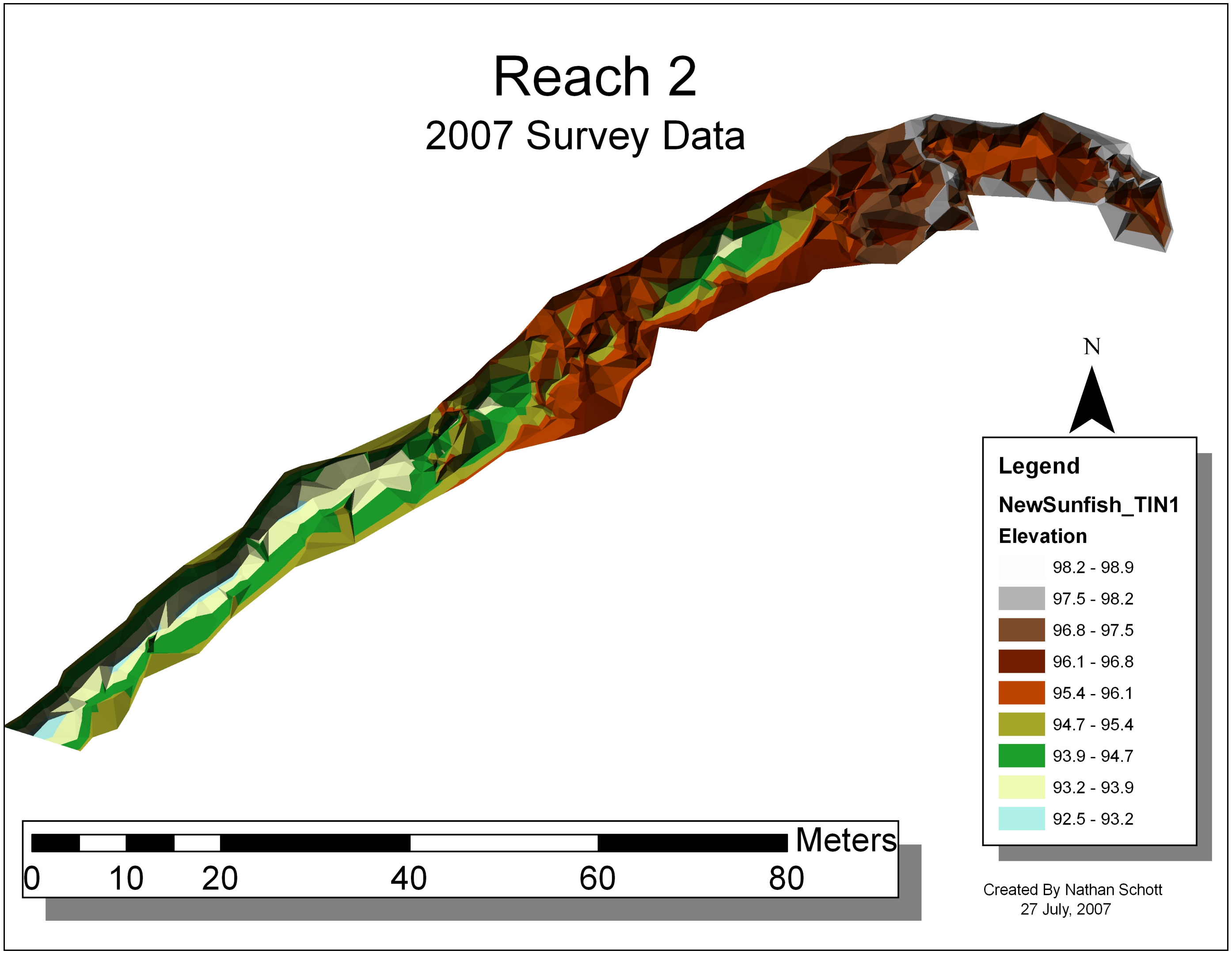

Figure 8. TIN of Reach 2, 2007 Survey Data

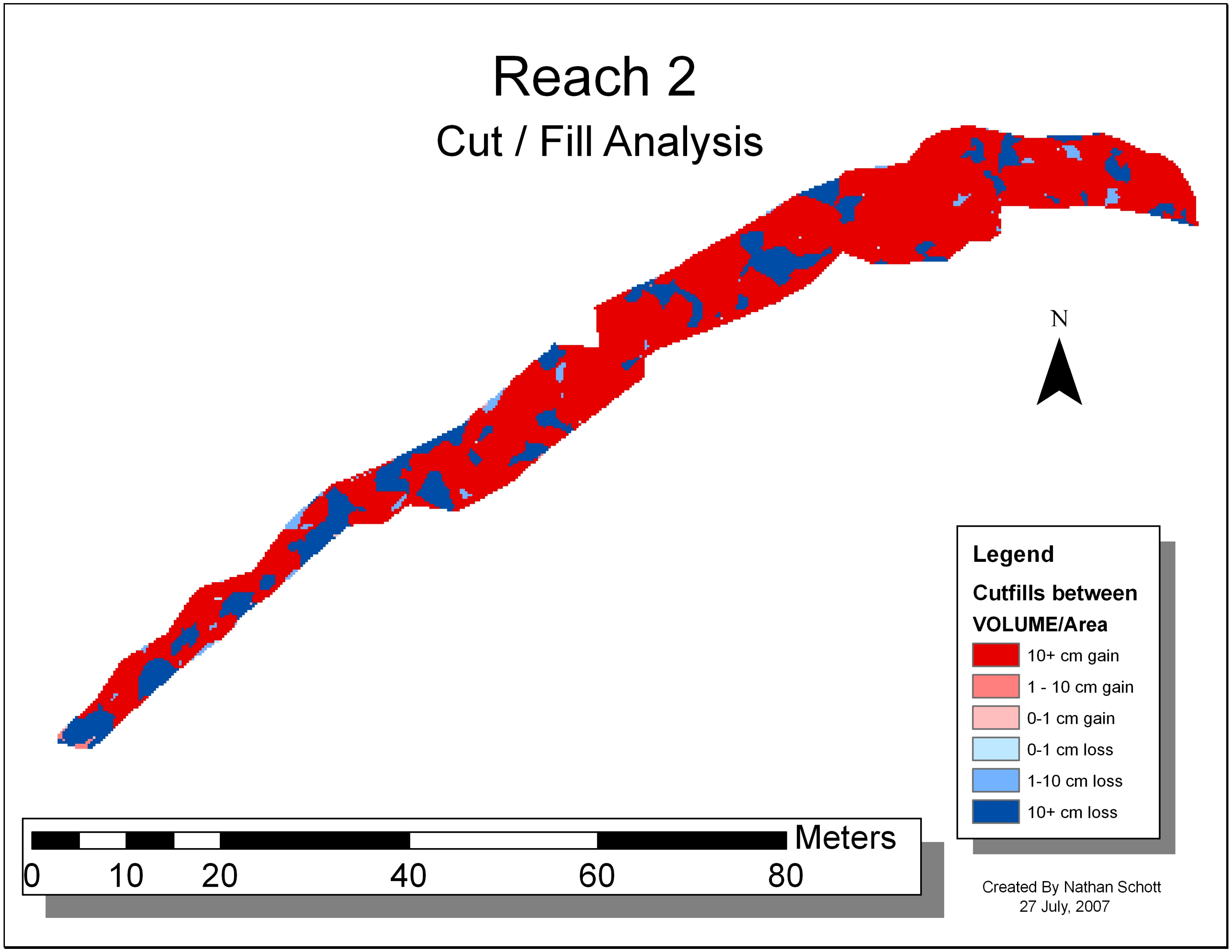

Figure 9. Cut / Fill Analysis of Reach 2

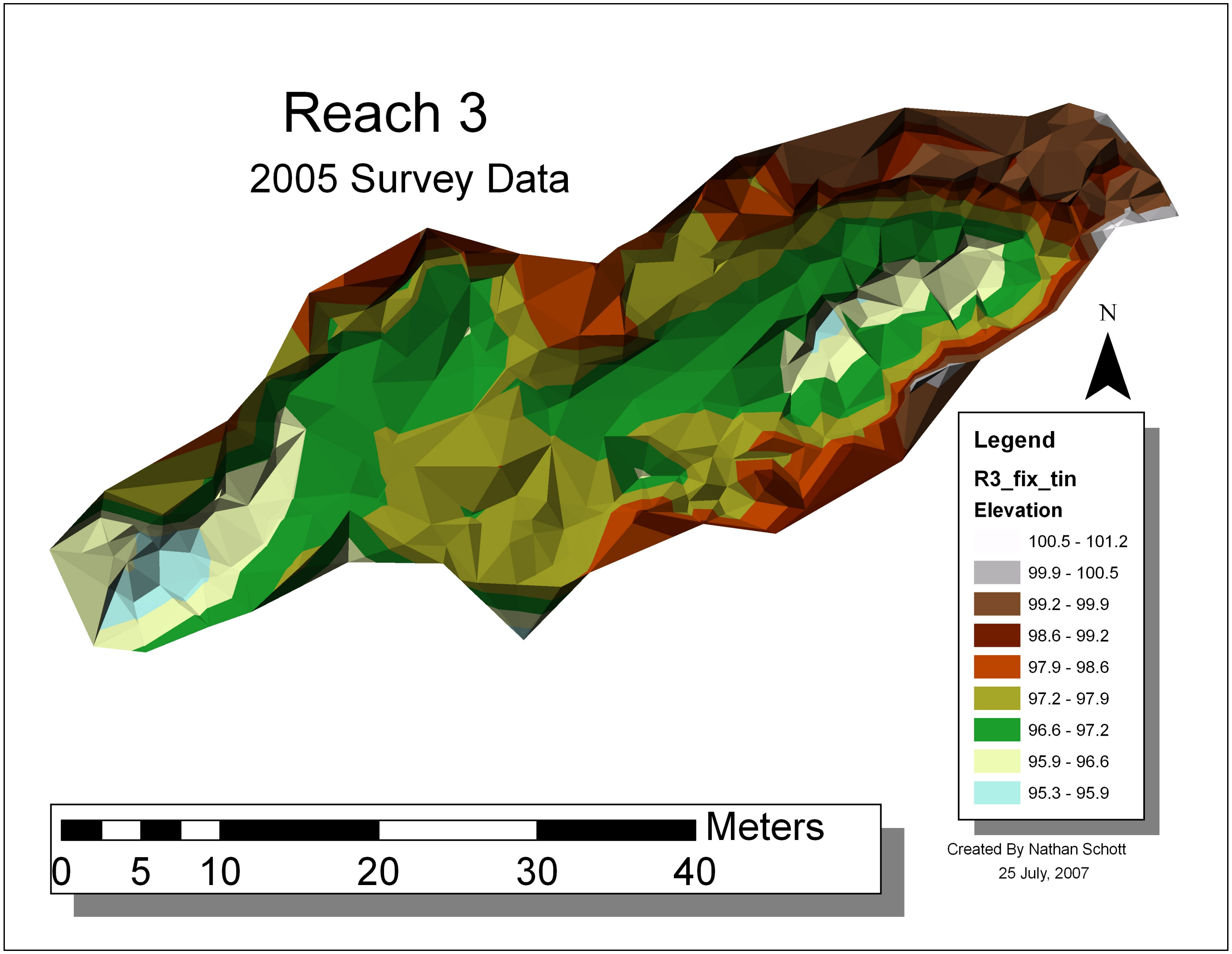

Figure 10. TIN of Reach 3, 2005 Survey Data

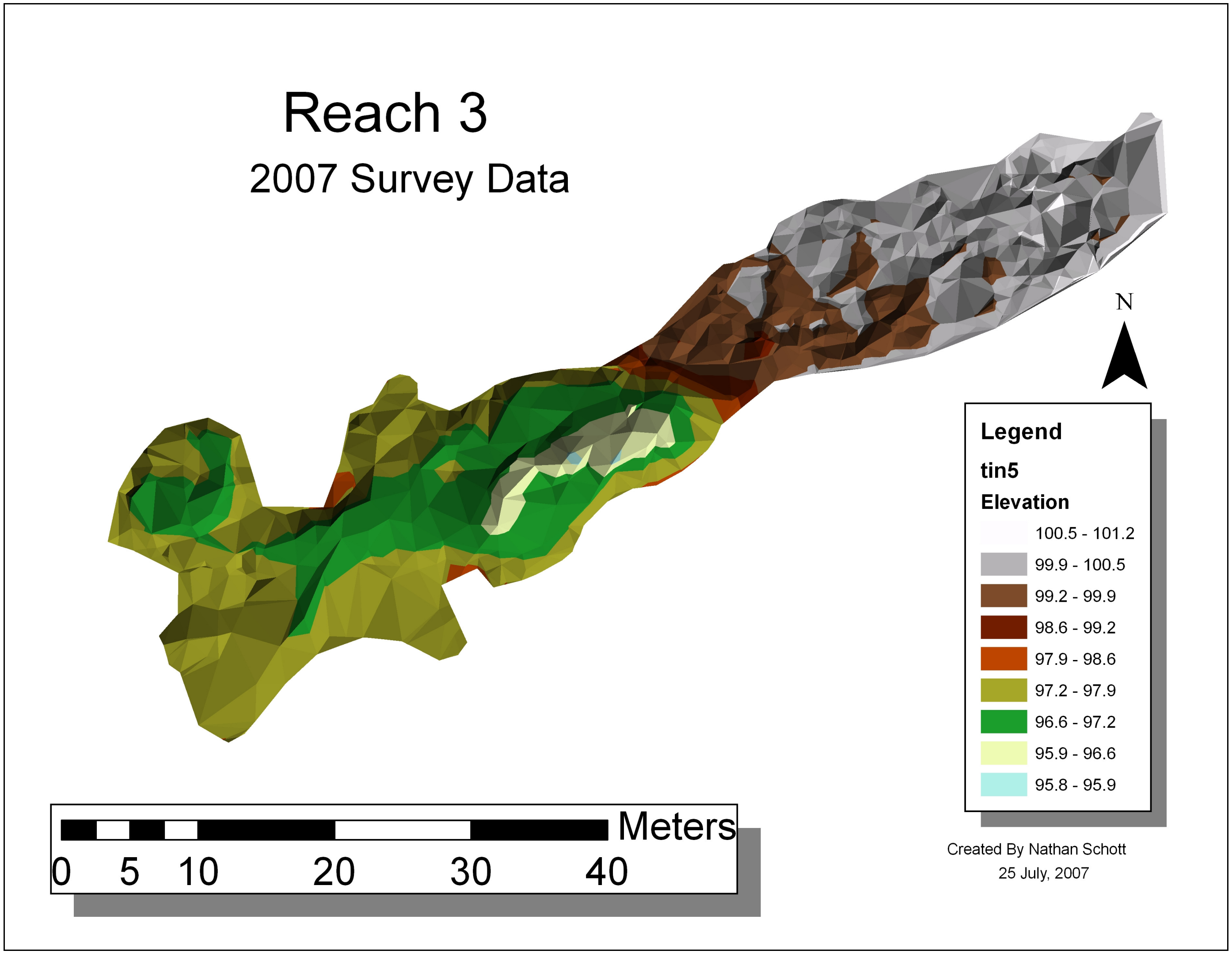

Figure 11. TIN of Reach 3, 2007 Survey Data

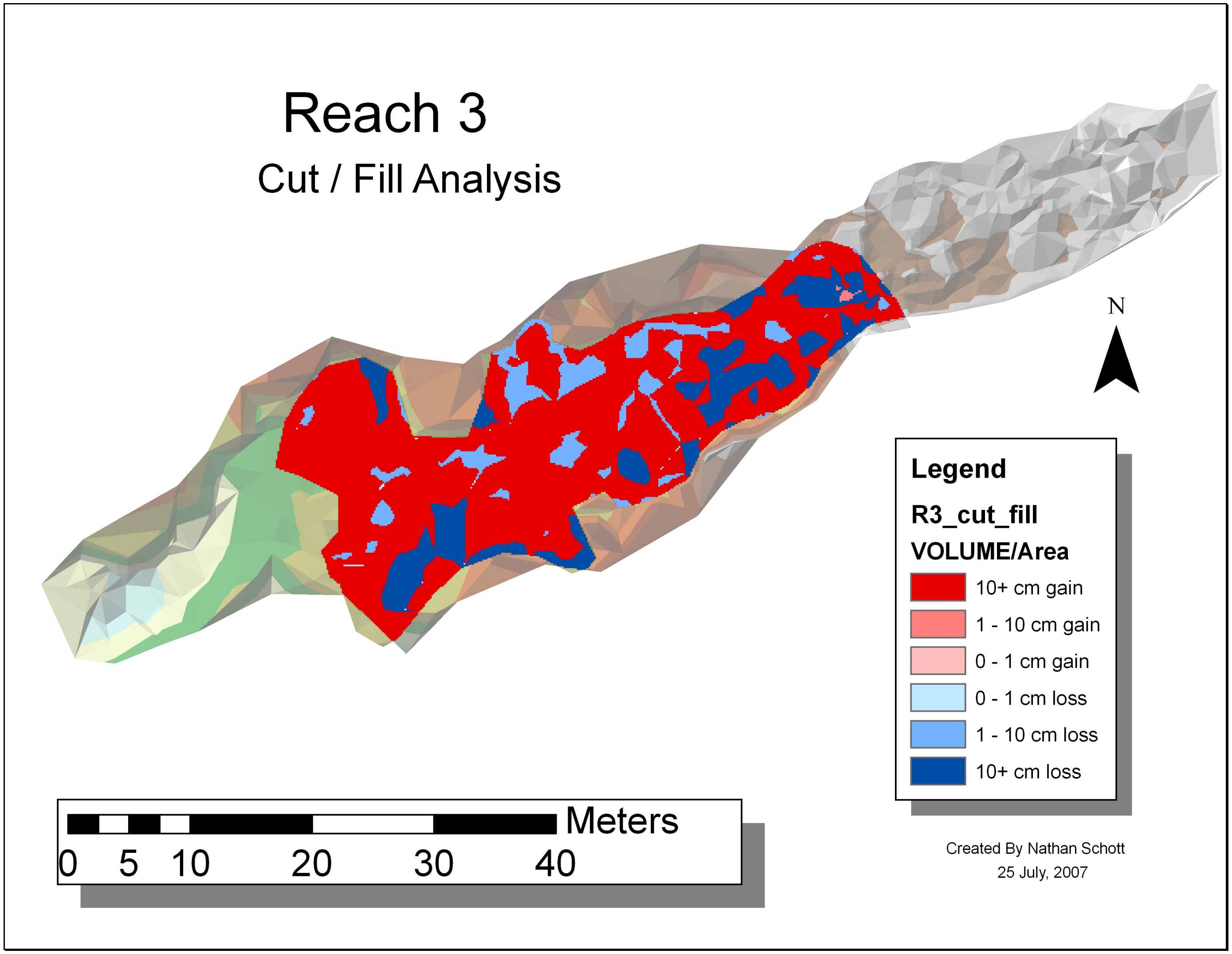

Figure 12. Cut / Fill Analysis of Reach 3

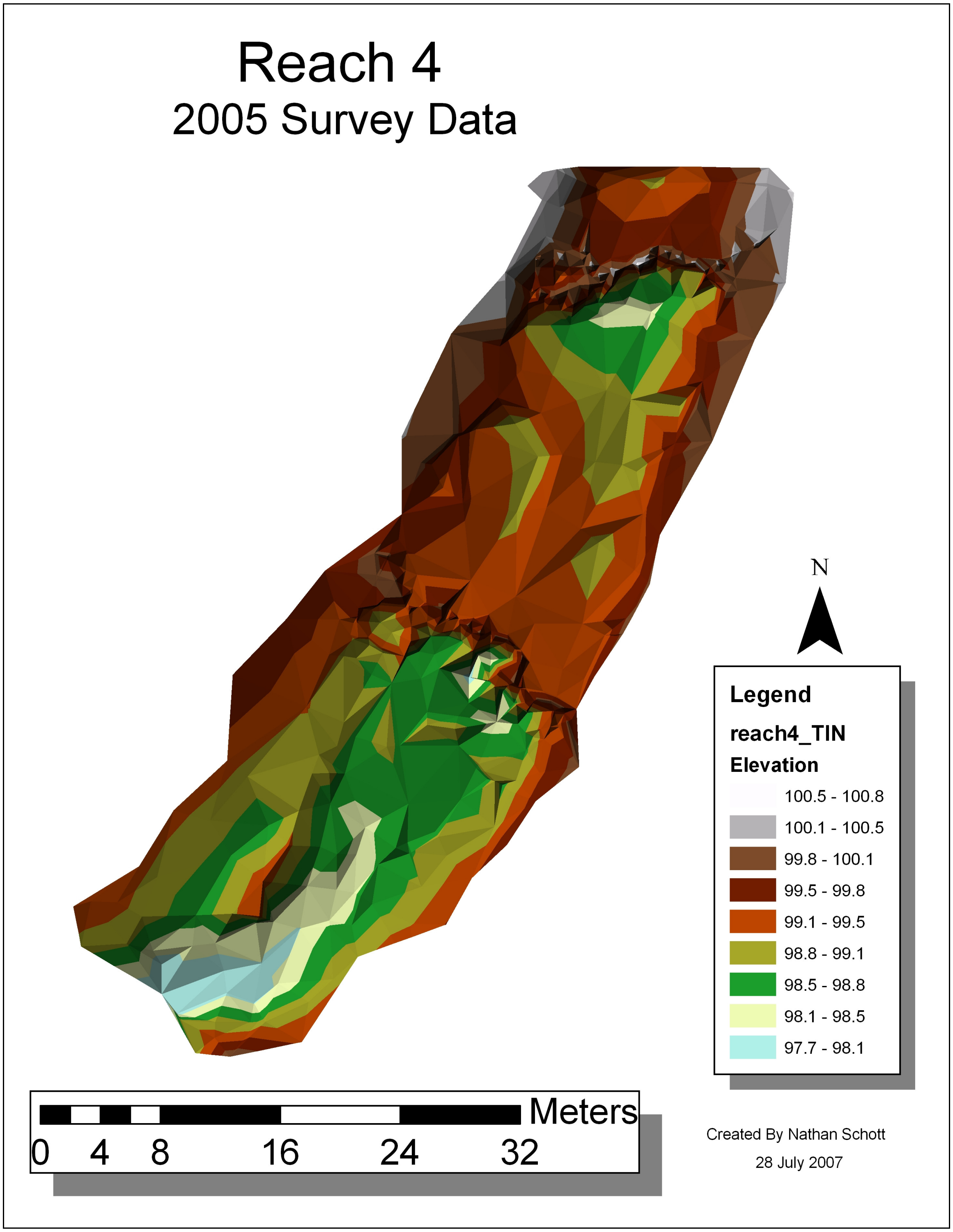

Figure 13. TIN of Reach 4, 2005 Survey Data

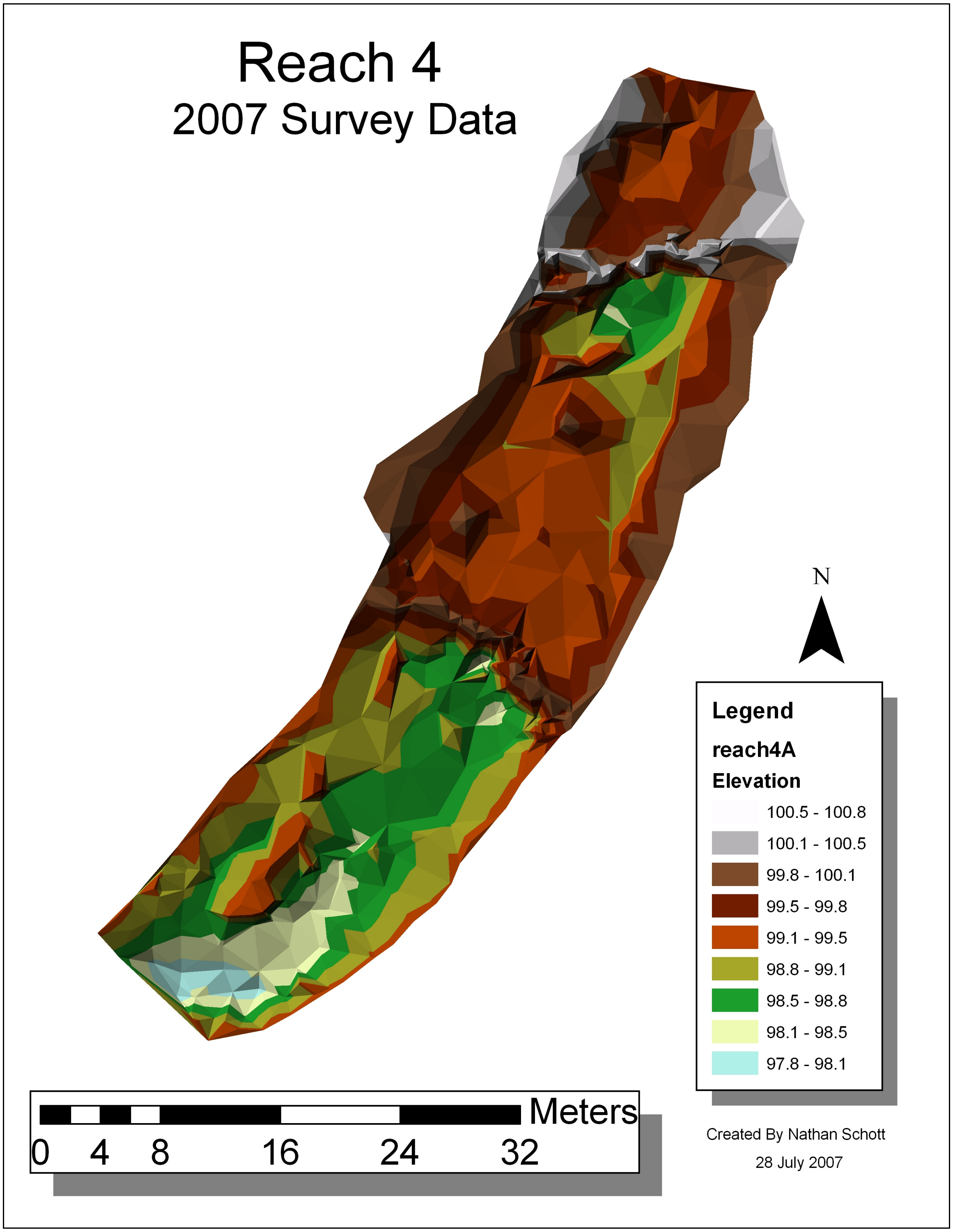

Figure 14. TIN of Reach 4, 2007 Survey Data

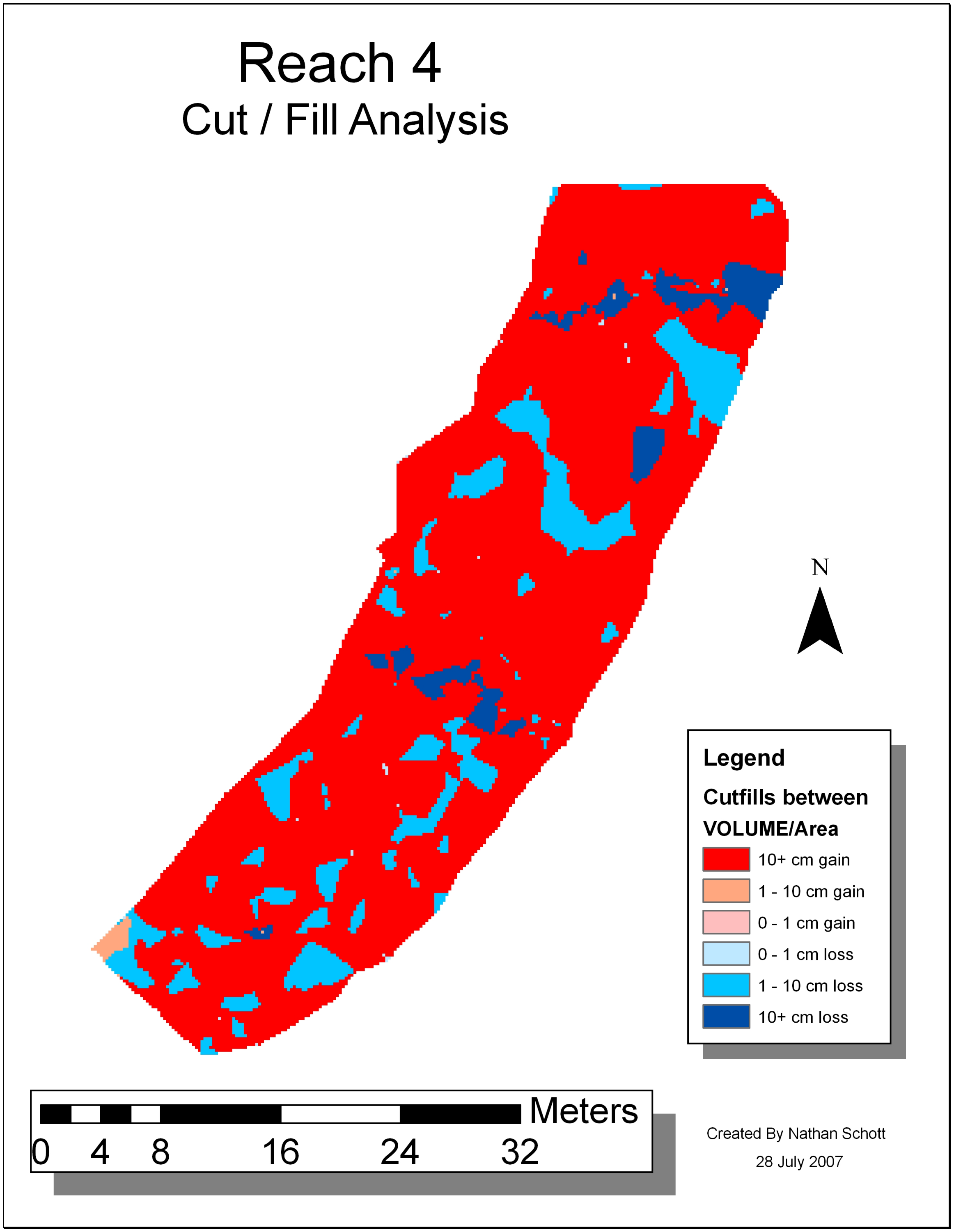

Figure 15. Cut / Fill Analysis of Reach 4

Discussion

The objective of this chapter was to determine how streambed and channel morphology respond to dam decommissioning activities. Because streambed and channel morphology at Fossil Creek are dominated by travertine precipitation rates and patterns, physical surveying was determined to be the most appropriate monitoring methodologies. While we see that this methodology has certain shortcomings, the physical surveying that took place at Fossil Creek was satisfactory at detecting change in channel form. From total station surveying errors reported by the Army Corps of Engineers (USACE, 2007), actual survey errors realized by backsite checks and accuracy of survey data compared to GPS located points, a detection limit of 10 centimeters was deemed to be appropriate. Evaluation of the physical monitoring methodology employed at Fossil Creek is based on three specific evaluation criteria identified earlier in this chapter.

1) Is it capable of detecting changes that are occurring in the system? For all intents and purposes, this methodology was capable of detecting changes in the streambed at Fossil Creek. The tops of travertine dams have been hypothesized to show the biggest changes in elevation over the survey interval. In reach 2, differences in the modeled surface of certain travertine dams have been calculated at one meter or more. In reach 3, the maximum differences detected were on the order of 0.5 meters and at Reach 4, maximum differences found were approximately 0.3 meters. Average aggradation rates were well over the 10 centimeters vertical error assigned for these surveys. Based on the maximum differences seen between surveys, average aggradation rates, and the errors associated with total surveying methodologies, this method was capable of detecting changes that occurred in the system.

2) Is it precise and accurate? Periodically conducting backsite checks throughout the survey provides an estimate of error associated with theodolite drift and changing atmospheric conditions. Unfortunately all four initial surveys did not provide backsite check data so the precision of that data cannot be determined. Post restoration survey did report on backsite checks. At Reach 2, backsite checks revealed a maximum vertical error of 2.0 centimeters and a maximum horizontal error of 0.5 centimeters. At Reach 3, a backsite check at the end of the survey reported a horizontal error of 0.3 cm and a vertical error of 0.4 cm. At Reach 4, several backsite checks were performed with a maximum horizontal error of 1.3 centimeters and a maximum vertical error of 0.4 centimeters.

Survey data can be checked for accuracy by measuring the distance between surveyed control points and the location of those points calculated from GPS data. At Reach 1, the combined distance between GPS located points and survey data was less then 8 centimeters. For Reach 2, that distance was less than 7 centimeters for initial survey data, and less than 5 centimeters for resurvey data collected in 2007. At Reach 3 we see a maximum distance between surveyed control points and those same points located by GPS of less than 2 centimeters for both initial survey data and resurvey data. Unfortunately, at Reach 4 overhead vegetation prevented accurate GPS location of control points and the accuracy of Reach 4 survey data cannot be determined.

3) Are the monitoring data of value to resource managers? As these data have recently been collected and analyzed and have not yet been made available to resource managers, the value of these data to resource managers cannot yet be determined. Speculating the answer to that question, these data alone will be of little value to resource managers. The greatest value these data contain are as an explanatory tool to help explain trends seen in other datasets. These data will be of particular use in explaining shifts in biotic populations as those occur. As altering geomorphic conditions may be easier for resource managers to alter than directly altering biological populations, the true value of these data can be realized. For example, if dust influx continues at Reach 4 and the pools fill-in with fine sediment, populations of invertebrates, and thus fish, may be altered. If the dust influx is causing shifts in biotic populations, eliminating the dust and letting biological populations recover may be easier than directly manipulating fish and invertebrate populations.

Because none of these monitoring data have been collected or analyzed in conjunction with other monitoring or research data at Fossil Creek, the true effectiveness of this methodology remains to be seen.

While the physical survey methodology was adequate at realizing changes in streambed form, several problems have arisen due to the unknown quality of initial survey data. Because backsite checks were not included in the initial survey data, the accuracy of these data is unknown. While it may be valid to assume that initial survey data accuracy is on par with resurvey data accuracy (+/- 2 cm), there is no evidence to validate that assumption. Additionally, problems due to resolution of initial survey data exist. Any map derived from interpolated elevations between actual points introduces some degree of uncertainty that interpolated maps are representative of actual channel form, regardless of interpolation techniques. That uncertainty can only be reduced as the interpolated distance between survey points is reduced. Thus, certainty in maps that interpolate elevations between actual measured points is directly related to point density.

Initial survey point density ranged from one point per every 4.6 meters to one point every 2.5 meters. Resurvey data were collected at a significantly higher point density, resulting in higher confidence that the maps derived from resurvey data are representative of actual streambed and of channel form. Because the two surveys collected data at different resolutions, the confidence that the calculated differences between the two surveys are actual differences in the streambed can only be equal to the confidence placed in the initial survey data. Thus, it is recommended that future survey data be collected at a resolution equal to or greater then the resolution of the survey data collected in 2007. This would result in detection limits of less than 10 centimeters and would allow for smaller changes to be detected in future surveys. The interval between surveys (~2 years) is adequate to see changes at the resolution collected by initial survey data. Shortening the survey frequency to once a year would still detect significant changes if the resolution of survey data was equal to or better than the resolution of resurvey data collected in 2007, especially in the reaches closest to the springs. Survey frequency any shorter then once a year is not recommended.

Chapter IV. Recommendations for Future Research

Next Steps

The objective of a restoration project is usually to restore a site to a condition similar to the one that existed before it was altered. This necessarily requires an understanding of the conditions that existed prior to that site being altered. At Fossil Creek, the establishment of reference conditions may be difficult because this site has been altered for almost a century. While early accounts of Fossil Creek do exist (see Lummis, 1891; Chamberlain, 1904), these accounts do not provide an adequate understanding of all predisturbance functions and the integrated physical, chemical, and biological characteristics of the system that are important in establishing reference conditions (Middleton, 1999). While exact reference condition may not be available for Fossil Creek, the continued monitoring of specific indicators can further inform managers of the state of the ecosystem and trends within that ecosystem.

With the dramatic increases in visitors to Fossil Creek triggered by full flow restoration, ecosystem degradation is likely to occur. Continued monitoring can help to determine the impacts of increased recreation. Continued research can help to understand ecosystem response to increased recreation. With managers armed with a better understanding of both the impacts of increased recreation and ecosystem response to increased recreation, further ecosystem degradation can be minimized.

The long-term validity of using dam removal as a restoration technique is something that has not yet been widely studied by the scientific community. Continued research and monitoring at Fossil Creek can help to advance the science of restoration ecology, and can help to validate dam decommissioning as a restoration technique.

Because of the better understanding that interdisciplinary approaches to research and monitoring can provide, their continued use is advocated. There is a unique opportunity at Fossil Creek to greatly improve the understanding of ecosystem response to decommissioning activities.

The downfall of many research and monitoring programs accompanying dam decommissionings is the lack of baseline data. At Fossil Creek, significant short-term baseline data have already been compiled during the highly impacted condition of Fossil Creek when the majority of flow was diverted away from the creek. The compilation of significant baseline data, and the fact that decommissioning and restorative techniques are spread out over several years allows for the effects of individual restoration activities to be quantified. The full-flow restoration and the exotic fish removal that occurred during the summer of 2005 were only the first of many restoration activities. Complete restoration, including the lowering of the Fossil Spring Dam and removal of accumulated sediment, will not be completed until the spring of 2008. It is recommended that intense interdisciplinary research and monitoring be continued throughout the decommissioning process, as well as the 2-3 years after decommissioning activities have been completed. This intense short-term monitoring will allow for the immediate response of aquatic and riparian ecosystems to be documented. This will go a long way toward understanding total ecosystem response to decommissioning activities. It is also recommended that a long-term research and monitoring program be implemented to document the response of ecosystem processes that operate at longer temporal scales. The information that can be conveyed from both intense short-term and long-term research and monitoring programs will not only aid in managing the system, but will greatly advance our understanding of ecosystem response to dam decommissioning activities. This increase in our understanding can go a long way to prove certain decommissioning activities as valid restoration techniques. All research and monitoring efforts should be interdisciplinary in nature for the various reasons provided in Chapter 2.

Funding for the continued existence of the Fossil Creek Ecosystem Studies Group at NAU is currently being sought. As this group has only been intact for about three years, understandings of the system have typically been restricted to disciplinary understandings. As mentioned before, it is only after a strong disciplinary understanding of the system has been achieved that good, collaborative interdisciplinary research can occur. It is strongly recommended that the interdisciplinary research team from NAU continue, and that the focus of this team should move to answering interdisciplinary research questions, especially those most pertinent to ecosystem management. It is also recommended that this interdisciplinary research team solicit input from the managers at Fossil Creek so that interdisciplinary research designs provide information that is of use to resource managers. A list of potential interdisciplinary research questions is provided at the end of this chapter (see Table 6).

Several researchers from the Fossil Creek Ecosystem Studies Group at NAU have applied for funding to continue interdisciplinary research and monitoring at Fossil Creek. The focus of this future work will be on understanding the ecosystem consequences of the dynamic geomorphology at Fossil Creek. While this research includes only two researchers from the Fossil Creek Ecosystem Studies Group at NAU (and three other researchers), this is exactly the type of interdisciplinary research advocated in the collaborative research model presented in this thesis. While the other researchers may require some time to become familiar with the processes at work at Fossil Creek, interdisciplinary work can proceed begin almost immediately after funding is secured. It is recommended that the other researchers of the Fossil Creek Ecosystem Studies Group at NAU secure similar funding for future interdisciplinary research and monitoring. Suggested interdisciplinary questions have been provided in Table 6.

While many other interdisciplinary questions can be formed, it is recommended that the questions of most value to resource managers be the first to be answered. This necessarily requires increased collaboration between researchers and managers. With little modification of current and scheduled research efforts, research findings can simultaneously serve two purposes: advancing the understanding of ecosystem response to dam decommissioning activities, and allowing management decisions to be better informed.

It is also recommended that federal and state agency personnel involved with research and monitoring programs at Fossil Creek be invited to participate in the interdisciplinary effort already underway. Increasing the number of datasets involved in an interdisciplinary effort increases the number of potential interdisciplinary questions that can be asked. While it is realized that government agencies may not have the flexibility to modify existing monitoring programs to be incorporated into a larger cooperative effort, even the sharing of understandings can help all researchers involved to better understand the system they are studying.

Evaluating collaborative research projects upon completion is of utmost importance. Not only should evaluative criteria focus on the collaborative process itself, but evaluative criteria also should assess research findings in relation to research objectives. The evaluative criteria found on standardized evaluations are a critical tool needed to make good comparisons between research projects. A common methodology for framing manuscripts is another recommendation that can ease comparisons between research projects.

Table 6. List of Potential Interdisciplinary Research Questions

What are the impacts of recreation on stream morphology? 1. What the impacts of riparian zone camping on stream morphology 2. What are the impacts of social trail networks on stream morphology? 3. How will the introduction of kayaking affect stream morphology?
What are the impacts of recreation on fish, invertebrate, or crayfish populations?
How will groundwater pumping or climate change affect travertine precipitation rates and patterns?
How will groundwater pumping or climate change affect fish, invertebrate, or crayfish populations?
How will an altered sediment flux affect stream morphology, or fish and invertebrate populations?
What are the affects of increased fishing on fish and invertebrate populations?
What are the links between increased recreation and water quality?
How will altering water quality affect stream morphology?
How will altering water quality affect populations of fish and invertebrate species?
What is the camping density along Fossil Creek and what are the links between camping density and stream morphology, fish populations and invertebrate populations?

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Appendix A

Standardized Email Sent to All Interview Participants

Dear (Participants Name),

My name is Nathan Schott and I am a grad student at Northern Arizona University in the Environmental Science and Policy department. I am writing to ask for your permission for a short interview about your involvement at Fossil Creek. I am writing my thesis on the effectiveness of the monitoring programs implemented prior to dam decommissioning and river restoration activities at Fossil Creek. The purpose of this work is twofold. First, my thesis will make recommendations on designing and implementing an effective inventory and monitoring programs for similar dam decommissioning and/or river restoration activities. This will be a synthesis of 'lessons learned' at Fossil Creek. The second purpose of this work is to understand the collaborative process that took place between the various federal and state agencies and report on both successful strategies and areas for improvement.

Attached is list of potential questions. Also attached is an informed consent document. If quotes are going to be used in my thesis, I will send you a copy of the quote in its context for your permission before printing. The interview will not be tape recorded.

I anticipate the interviews taking approximately 30-45 minutes. This interview can take place over the phone or at another location, whichever you would prefer. If you would be willing to participate in this study, it would be greatly appreciated. Thank you for your time and your cooperation.

Sincerely,

Nathan Schott
Northern Arizona University
Box 5694
Flagstaff, AZ 86011-5694
(928) 523-5705

Appendix B

List of Potential Questions to be Asked During Interviews

Survey instrument for researchers at Fossil Creek

How long have you been involved with your monitoring/research program at Fossil Creek?

I understand that you have been looking at ________ down at Fossil Creek. Could you please explain exactly what you are looking at what you expect to find?

Would you consider what you are doing research or monitoring?

How did you arrive at your monitoring/research design?

Do you feel that your research/monitoring program is part of an effort to answer bigger, interdisciplinary questions, or more of an individual effort?

This is a two part question First of all, what sort of baseline data did you collect prior to the start of restoration?
Do you feel that baseline data was sufficient?

What are your results to date, and have they met your expectations?

If you were given the opportunity to do this sort of thing again, would you do anything differently?

Is there anything else you would do to improve your monitoring/research program?

Survey instrument for understanding collaboration

Prior to initiation of the monitoring/research project, was there any sort of collaboration with anybody outside of your agency regarding the project?

Did you feel like more like you were part of a bigger research design at Fossil Creek, or more like an independent project?

Is there any sort of data sharing that you are aware of between the various stakeholders at Fossil Creek?

Would you be willing to collaborate with other agencies about your monitoring/research project?

Obviously building trust would be important in any sort of data-sharing scenarios, what level of trust do you have now with other researchers/managers?

What would be the most effective ways in which trust could be increased?

Do you think that collaboration could possibly make your research/monitoring program more efficient?

Do you feel like your research/monitoring program would benefit with access to other monitoring/research data collected?

What sort of collaboration would be beneficial to your particular situation?