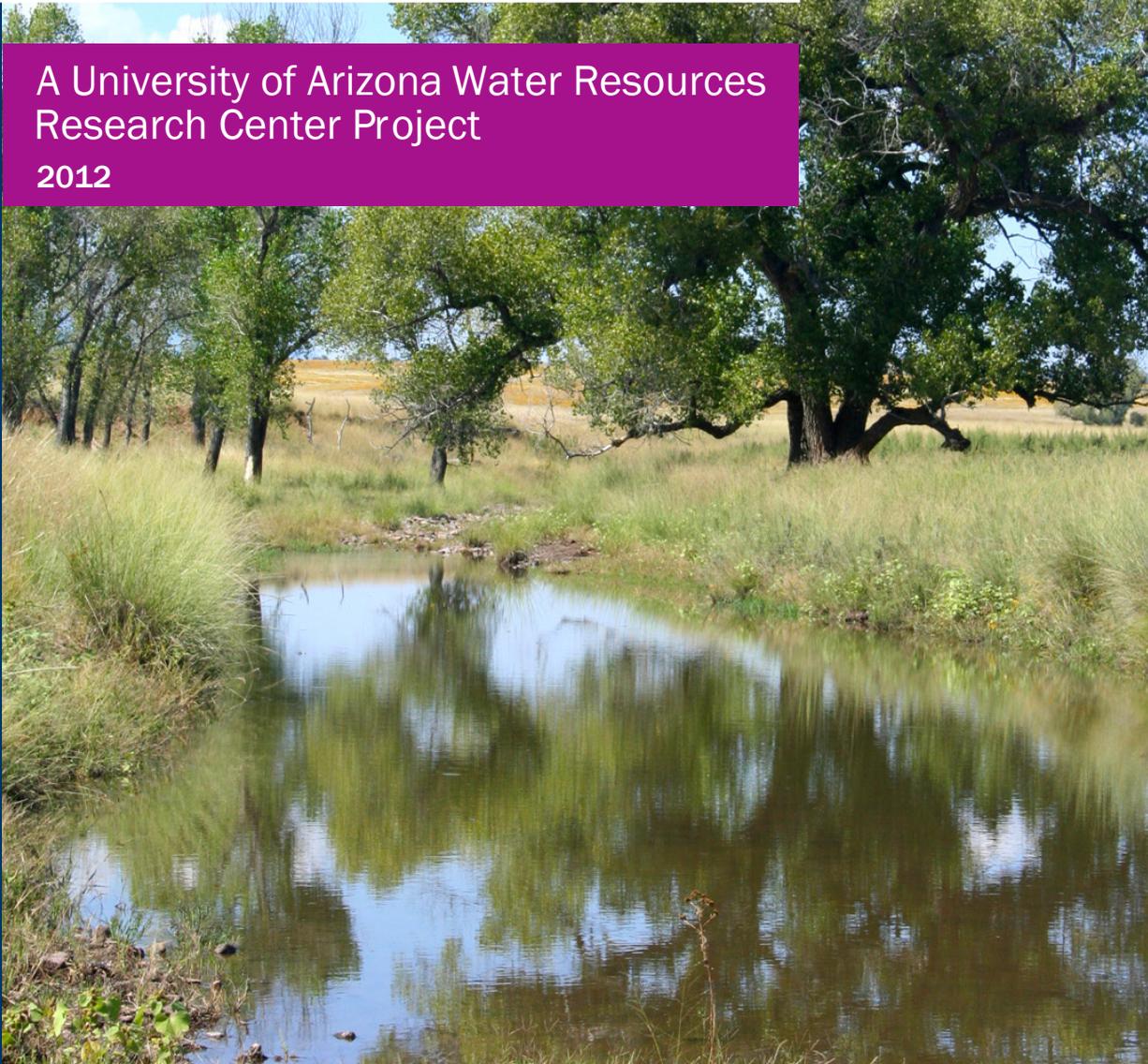




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Arizona Environmental Water Needs Assessment Report

A University of Arizona Water Resources
Research Center Project
2012



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The mission of The University of Arizona's Water Resources Research Center is to promote understanding of critical state and regional water management and policy issues through research, community outreach, and public education.

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EXECUTIVE SUMMARY

Considering environmental water needs alongside human demands is an emerging paradigm in water policy. The science of environmental water needs (or e-flows) is ever growing and evolving. And yet, no compendium of efforts to define e-flows in Arizona had been compiled, until now. This Assessment Report describes the geographic location and focus of nearly 100 studies of environmental water needs in Arizona, using all relevant sources. It identifies environmental water needs for some rivers and denotes the Arizona rivers where we know little. Defining environmental water needs is the first critical step in the broader process of securing and addressing environmental flows. Through this Assessment Report and the companion Arizona Environmental Water Needs Methodology Guidebook, we aim to clearly describe the science of environmental water demands.

Plants and animals need water to survive and carry out basic functions, like reproduction. Even more, that water must arrive in the right quantity, place, and time. We as humans plan for our own water use - we store and protect the water for drinking, domestic use, landscape irrigation, agricultural production, and industrial manufacturing. But we must also plan for nature if we want to ensure that the plants and animals of the state have enough water to survive and thrive. Quantification efforts will help inform water planning efforts and establish the environment as a water using sector where the law may be limited. They also improve our basic understanding of ecosystems on which we depend.

Water flow through a riparian (river banks and terraces) or stream area consists of five components: the magnitude, frequency, duration, timing, and rate of change of flow. Each one of these elements has the power to impact water quality, energy sources, physical habitat, and biotic interactions within the ecosystem. When any one of these components changes, it creates a ripple effect in the ecosystem and changes the ecological integrity of an area.

The 93 studies reviewed all provide some indication of environmental water demands in Arizona. All of the studies demonstrate the connection between water availability and ecological health. Researchers studied flows needed to maintain healthy aquatic (in-stream) ecosystems, healthy riparian areas, or both. Some studies rely on historical flow patterns to define flow needs or demonstrate relationships between ecological components and elements of a natural flow regime. Some studies collect field data, perform statistical analyses, and use spatial mapping to study flow-ecology relationships. Others rely on expert analysis of published literature to identify ecologically important components of flow regimes. Finally, several studies quantify the social or economic value of the environment, which can then be linked to the water needed to preserve those human-valued ecosystem elements.

The majority of Arizona e-flow research found in our inventory examines the water needs of riparian elements by themselves. The water requirements of riparian trees and shrubs have been studied the most extensively, both in terms of geographic extent and number of studies. Water requirements for both riparian and aquatic species have only been studied together for a handful of streams. Amphibians, mammals, and reptiles have been studied the least often. The most commonly applied method in Arizona environmental water needs studies involves correlating flow attributes with ecological responses.

Researchers have most extensively studied the water needs of Arizona's riparian plants, quantifying plant water use, depth to water limits, and needed flood events. For example, riparian vegetation on the San Pedro River is estimated to use around 10,000,000 m³/yr (8,100 AF/yr) of groundwater. Several studies demonstrate an important connection



Sonoita Creek Natural Area.
Photo Credit: Arizona State
Parks

between water available to riparian vegetation and the health of insects and birds. Others indicate the flow and water temperature needs of native fish. Hautzinger et al. (2006) is the only study in the inventory that provides quantitative flow prescriptions for all five components of flow, and that study was conducted specifically for the Bill Williams River. Other river basins, like the Santa Cruz, have at best small scale studies that prescribe flows for a single stream reach.

At a statewide scale, the picture of environmental water needs is not complete. Despite the fact that there are perennial (always flowing) streams in every river basin across the state, many have not been studied extensively, if at all. Forty studies of environmental water needs have been performed on the San Pedro River basin, while no studies have been published for the Little Colorado River basin. Most basins have fewer than 10 studies on environmental water needs, providing a somewhat limited starting point for intra-basin analysis. In basins where only one study has been done on each taxonomic group, findings about flow needs have lower confidence. This inventory of studies provides quantitative information about the flow needs and flow responses of every riparian and aquatic taxonomic group, but not necessarily every aquatic and riparian species in Arizona. Plants, fish, and birds have been studied the most. Knowing the water needs of just a few species, but not all, limits the manager's ability to ensure flows will protect the whole ecosystem.

The importance of water to riparian areas has been aptly demonstrated; not only is groundwater availability for baseflows necessary to sustain riparian flora and fauna, but well-timed flood flows are critical to distribute biota and sediment. Although less studied than riparian systems, aquatic ecosystems are equally dependent on complex interactions among components of flow. Native riparian and aquatic species have specific tolerance ranges for alterations of environmental flow parameters. Several key aspects of flow regimes, including water temperature and water quality, have been shown to be important for aquatic and riparian health in the Verde River system. Water managers in river basins with limited resources identifying critical flow thresholds for ecosystem health may need to look to other basins for initial guidance. Where researchers differ in the ways they measure flow elements, it will be difficult to compare findings across basins until standard measures are chosen.

More studies are needed that consider the water needs of both aquatic and riparian species in tandem. Additionally, given the proven influence of groundwater on aquatic and riparian ecosystems, most river basins (with the exception of the San Pedro and the Santa Cruz) could benefit from additional studies of groundwater influences on ecosystem health. Finally, if acceptable mechanisms for transferring findings from one river basin to another can be found, much of the existing work can be extrapolated across the state, saving the need to repeat what are often lengthy, resource-intensive studies.

Future work quantifying environmental flow needs will need to be complemented by compiling information about water availability and hydrologic patterns across the state. Areas of conflict or overlap between environmental water demands and other water uses may be priorities for future investigations. Those additional elements will ensure successful water planning and decision making around the state. Discussions will be necessary to make informed choices about the future of using our shared water for the environment, for our communities, and for our economy. It is our hope to facilitate a statewide conversation that includes all water sectors at the table.

Readers' Guide

For the layperson/general public: In this Assessment Report, you will most likely be interested in the Introduction (specifically the geographic context), the Qualitative and Spatial Analysis, the Findings by Basin and Additional Comments. Also, be sure to check the glossary for definitions of any unfamiliar terms.

Look for definitions and unit conversion factors in the sidebars like this

For the water manager: In this Assessment Report, you will most likely be interested in the Introduction (specifically the policy context), the Qualitative and Spatial Analysis, the Findings by Basin and Additional Comments. You might be interested in the Information Gaps and Next Steps. Also, be sure to check the glossary for definitions of any unfamiliar terms.

For the scientist: In this Assessment Report, you will most likely be interested in the Role of the Assessment section of the Introduction, the Summary of Studies, the Information Gaps and Next Steps. You might want to read the Policy Context as well.

I. INTRODUCTION

The goal of this assessment is to assist in bringing the environment to the table as a water user. In Arizona, water is a critical and controversial topic. Policy discussions about water often weigh domestic needs with those of agriculture or industry, but rarely consider the water needs of the environment. To remedy that oversight, researchers have spent years describing environmental water demands to better understand the vulnerability of the natural system and the impacts of water management strategies. The science of environmental water needs (or e-flows) has evolved from methods that focus on one aspect of flow to those that consider the needs of an entire river ecosystem. Until now, no compendium of efforts to define e-flows in Arizona had been compiled.

In this Assessment Report, we describe the geographic location (where) and focus (what) of nearly 100 environmental water needs studies in Arizona. By evaluating these studies, we identify the better understood environmental water needs of some rivers and note the many Arizona rivers where we know little. We identify relevant sources that describe current environmental water needs in Arizona and include most of them in our analysis. Any work of this nature is simply a snapshot in time as new efforts to define water needs for the environment emerge frequently. This report describes the state of knowledge at the time of its completion.

Describing environmental water needs is the critical first step in the broader process of securing and addressing environmental flows. Environmental water needs can be defined as flows needed to maintain geomorphology, water quality, support riparian (floodplain and bank side) vegetation, or maintain aquatic (in-stream) biological processes. Some studies describe the water flows that support a single animal or plant species, while others describe the water flows that support an ecosystem. Some focus on the importance of floods in maintaining the right balance between native and introduced populations, while others focus on the minimum flows needed to preserve habitat. Taken in sum, all these components of river and riparian ecosystems need to be preserved for the system to function (Poff et al. 1997, 769-784).

Through this assessment and the companion Arizona Environmental Water Needs Methodology Guidebook, we aim to clearly describe the science of environmental water demands. The purpose of this compilation and synthesis of available information is to serve as a tool for individuals, organizations, communities, and public officials to better understand, and ultimately to address, environmental water demands. These tools are intended to inform researchers, policy makers, and interested Arizona citizens about both the current knowledge and information gaps we have in our understanding of Arizona's environmental water needs.



Verde River, Sedona, AZ. Photo credit: Brittany Choate

WHY THE ENVIRONMENT NEEDS WATER

At a young age, we are taught about water – its many forms, where it comes from, where it ends up. We learn through classroom and firsthand experiences that water is essential for all living things. As adults, we see reports about the global water crisis or even hear researchers predicting that severe droughts will affect Arizona (Morello 2010). We know that like us, most of the animal and plant species in Arizona are dependent on our rivers, streams, and groundwater basins (Poff et al. 1997, 769-784). Aquatic and riparian species are adapted to the natural flow dynamics of streams, springs, and groundwater. This means that alterations to the natural flow regime put Arizona's native plants and animals at risk.



Lower Salt River, Mesa, AZ.
Photo Credit: Brittany Choate

Plants and animals need water to survive and carry out basic functions, like reproduction. Moreover, that water must arrive in the right quantity, location, and time. We as humans plan for our own water use - we store and protect the water for drinking, domestic use, landscape irrigation, agricultural production, and industrial manufacturing. But we must also plan for nature if we want to ensure that the plants and animals of the state have the water they need to survive and thrive.

Protecting biodiversity is key to protecting human health (Keesing et al. 2010, 647-652). Healthy river and riparian ecosystems provide basic ecosystem services we all need to survive. Trees create the oxygen that we need to breathe and shade to give relief from the heat. Riparian areas provide flood protection and filtration of chemicals from the water. Arizona's local economies rely on functioning natural environments in general and for tourism in particular. Attracting new, greener industries for economic development will require demonstrating an environmental ethic (Florida 2002).

Arizona faces an era of water management that may require simultaneously adjusting to long term drought and growing water demands. While we know on a deeper level that all water users should be considered, our focus on meeting immediate human needs may be to the detriment of natural systems. Streamflows around the region have been severely diminished due to human activity, which in turn has led to impaired biological communities (Carlisle et al. 2010). In order to identify strategies for a sustainable water future, we need solutions that satisfy environmental water needs alongside human needs. This requires an increased understanding of complex aquatic and riparian systems, in terms of the ecological effects of altered streamflow, and defining environmental water demands in terms used by other water sectors. Without this information, we may never reach the point where environmental values and human activities can truly coexist (Richter et al. 2003, 206-224).

Many researchers have set out to answer the question – does the environment need a legally ensured allocation of water, and if so, how much water does it need? Scientists in Arizona and across the Western United States have spent years trying to describe environmental water demands to better understand how water influences all other living things. By understanding our river and riparian ecosystems, we can be aware of natural limits and the impact of water management plans and strategies. Science can be useful to inform people of the management options and their associated tradeoffs. This report compiles and synthesizes a collection of efforts to define e-flows in Arizona, providing a tool for Arizonans to make informed choices about water resources and the natural environment.

POLICY CONTEXT

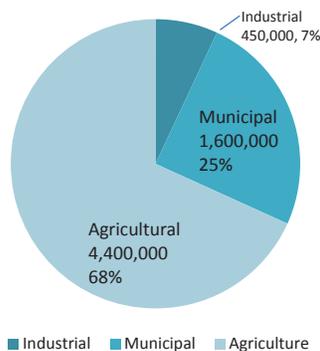
Quantification of environmental flows will inform water planning efforts and establish the environment as a water using sector where the law may be limited. In Arizona, as in most Western states, surface water laws are governed by the tenet of prior appropriation, also known as the “use it or lose it” principle. This has impacted the state's ability to intercede on behalf of the environment and preserve instream flows (Megdal, Nadeau, and Tom 2011). The Groundwater Management Act (GMA) was established in 1980 to conserve, protect, and allocate the use of groundwater resources in designated areas of the state. While this Act offered indirect help with environmental water needs, the Assured Water Supply (AWS) Program only considers anthropogenic water needs in restricting new development in highly populated areas like Phoenix and Tucson.

The Governor's Water Management Commission (2001) recommended measures to improve riparian protection in Arizona, but aquatic and riparian areas have no recognized rights to water under Arizona's water management system. One option for securing water for the environment involves applying for an instream flow right permit. To receive an instream flow right in Arizona, one must demonstrate that streamflow is being used by fish, wildlife, or recreation activities. This is an option that The Nature Conservancy and several federal land managers have exercised for streams around the state.

One new voluntary program is being piloted that will provide funding support for both instream flow protection and riparian restoration projects by engaging individual water customers that care about the environment (Megdal, et al. 2009). Conserve to Enhance (C2E) is a voluntary water conservation program that seeks to link municipal consumer behavior with environmental benefits. Participants in C2E will commit to implementing new, water saving practices and in return are encouraged to donate some or all of the money they save on their water bill to riparian enhancement projects selected by the C2E program advisory board. This program can provide a source of funding for securing water for the environment. Despite isolated efforts like instream flow rights programs, there is currently no statewide protection for environmental flows.

Arizona is one of only a few western states without a statewide water plan. The Arizona Department of Water Resources (ADWR)'s compendium of statewide information about available water supplies and human demands, the Arizona Water Atlas, could be used to facilitate statewide water planning (Arizona Department of Water Resources (ADWR) 2009). However, the Water Atlas does not include environmental uses in the summaries of statewide water demand (Figure 1), except for estimating effluent use by created wetlands in limited instances.

Figure 1. Summary of Statewide Water Demand
(Source: Arizona Department of Water Resources)



*Colorado River on-river diversions are 2.046 Maf of which 0.75 Maf is returned to the system for other use. Demand does not include CAP long-term storage and system losses (approximately 0.3 Maf) or environmental demand on the Colorado River (approximately 0.02 Maf)

The last chapter of the Water Atlas, ADWR's vulnerability assessment, when completed, will interpret and evaluate Atlas findings to support water management decision processes, specifically in terms of supply vulnerability and resource sustainability. Their vulnerability assessment will identify areas with current or projected demands that exceed supplies. This assessment will also identify areas in competition with environmental demands or the potential for environmental impact.

It has been said that "an ideal assured-water supply law... [must] be interconnected with broader planning mechanisms for land, water and environmental protection" (Bates 2008). However, all states working toward understanding environmental flows face a challenge as "there is no universally accepted method or combination of methods" for defining water needs— every environment requires a different approach (Annear et al. 2004). Most fish and wildlife management agencies in the United States do not have

experience applying even the most commonly used flow methods (Annear et al. 2009, vii). Finding this balance is something that the state of Arizona will need to attempt as it develops a sustainable water policy.

The concept of assessing environmental water needs is not new. In fact, many states have already seen the value in understanding environmental water requirements and are using their knowledge to induce both political and scientific changes. Application of environmental water requirements to state policy frameworks varies. States with policies regarding environmental water needs include California, Colorado, Florida, Georgia, Idaho, Texas, and Washington. Several states condition issuance of new water use permits on whether the use can coexist with needed instream flows (Megdal, Nadeau, and Tom 2011). In Florida, in addition to being used in the permit process, minimum flow levels are used as benchmarks to determine water shortages, water supply sources, and when recovery plans are needed (Megdal et al. 2009, 1-20). Other states are introducing new or improved environmental flow policies through statewide water planning processes (e.g. California, Georgia). Idaho protects and maintains state-owned water sources when it is deemed to be "in the public interest" (Kiefer 2008).

These states also differ in their scientific standards for defining environmental water needs. Using a dynamic flow regime is recommended in California (Environmental Defense 2004). Colorado currently uses minimum flow levels, and the state is working to acquire enough water rights so they can return waterways to their natural flow levels (Colorado Water Conservation Board (CWCB) 2007). Current policies in Texas (Bradsby 2009, 1-18) and Florida

(Megdal et al. 2009, 1-20) recommend using minimum flow levels to protect the environment's water supply. However, science teams in Texas have been asked to develop a recommended environmental flow regime for each basin (Bradsby 2009, 1-18), and some of Florida's Water Management Districts have chosen to define a long-term hydrologic regime for their region (St. Johns River Management District 2010). This review of states considering environmental water needs is by no means comprehensive, but each example demonstrates progress in inviting the environment into water policy discussions and scientific evaluations.

THE ROLE OF THE ASSESSMENT

The science of e-flows is one tool in the water management toolbox. E-flow decision tools can describe tradeoffs inherent in allocating more or less water for nature. Because water allocation decisions reflect societal values, science alone cannot inform choices about the desired condition of the natural environment. E-flows science can indicate how much water would be needed to meet a given ecological objective. Thus, this assessment is intended to inform water policy and decision making at local and statewide levels.

Water-related ecological objectives need to be quantitatively defined so that they can be integrated with other water management objectives. One way to start quantifying ecological objectives is to identify currently protected environmental uses of water, such as instream water rights claims and restoration sites. Then the water needed for human uses can be compared with water needed for environmental objectives (Richter et al. 2003, 206-224). This is similar to the approach taken by the Water Resources Development Commission and its Working Groups. In 2010, the state legislature created the Commission to determine the future water demands and supplies of Arizona and make recommendations on any studies or legislation needed to safeguard our state's water supply. Notably, the Commission considered the current water demands of the environment alongside other water sectors, through the efforts of its Environmental Working Group.

In addition to supporting environmental water uses that already have legal protection, Arizona's citizens may choose to preserve or restore as yet unprotected flows associated with other environmental benefits. A Gallup Arizona Poll, conducted in 2008, revealed that protecting Arizona's natural environment, water supply, and open spaces are high priorities for Arizona citizens. In fact, citizens specifically favor adopting a water management plan that protects water supplies for the entire state (The Center for the Future of Arizona 2009).



Oak Creek, Sedona, AZ. Photo credit: Arizona State Parks.

In addition to informing water policy, this assessment is also intended to assist the many ongoing efforts across the state to quantify environmental water needs. By assembling available information about Arizona's environmental water needs, we identified key information gaps and the science tools that might be employed to fill those gaps. In part, this compilation of studies provides a resource for researchers to connect with others doing similar work. Ultimately, improving scientific knowledge and technical capacity to quantify Arizona rivers' e-flows will include developing classifications of rivers that guide the application of flow findings from one river basin to the next.

GEOGRAPHIC CONTEXT

When asked to think of a riparian area or a stream, people may conjure up an image of water, a few trees and maybe an animal or two. While these elements exist in a number of riparian and stream areas, they appear as only a surface view of the actual intricacies that compose a waterway. An alternative perspective would be to think about the water moving through the area in terms of five components: magnitude, frequency, duration, timing, and rate of change in water flow. Each one of these components has the power to impact water quality, energy sources,

physical habitat, and biotic interactions within the ecosystem. When any one of these components changes, it creates a ripple effect in the ecosystem and changes the “ecological integrity” of an area (Poff et al. 1997, 769-784).

To understand the complex nature of a flow regime, one must know the definition for each of the five flow components. Magnitude of a waterway is how much water passes by a single location in a set timeframe. The frequency is the number of times a particular flow event occurs during a set time interval. Deviations can occur with rainfall events or a dam bursting. The duration of flow for a waterway is how long a certain flow level lasts. For example, there may be a flood event that lasts for a few days or a steady snow melt that lasts for a few months. The timing of flow refers to when the flow occurs, and during which seasons. And, finally, the rate of change is how long a stream segment takes to change between two magnitudes. All of these factors must be considered to determine how flow alterations impact an ecosystem (Poff et al. 1997, 769-784).

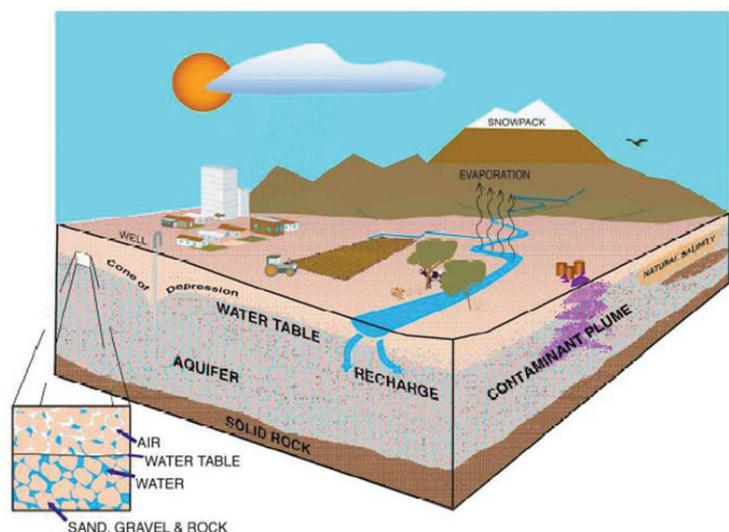
Water managers can help to protect ecological functions in state streams and rivers if they consider environmental water needs and attempt to maintain a relatively natural flow regime. A natural flow regime includes all flow events that support river-adapted ecosystems, such as “periodic flooding and the regular occurrence of high and low flows, which trigger physiological and behavioral responses of aquatic and terrestrial species that are intimately linked to these physical changes in water level” (Mulvaney 2009, 315-337). A dynamic flow regime provides diverse benefits to river ecosystem health because floods support aquatic and terrestrial food webs, fish migration, and spawning while minimum low flows help maintain water temperature, quality, and allow fish to move to feeding and spawning areas. The natural system responds to disturbance processes—habitat is altered and created regularly through fluctuations in water levels. For example, a flood event can scour bottomland vegetation and create pools of water in higher areas.

Ecosystem health suffers when the natural flow regime is not maintained. Without regular flooding or high water levels, fish cannot access upstream, side channel, or floodplain areas, which are necessary to support life cycle elements such as reproduction, development of juvenile stages, and other migratory behavior. The absence of high waters allows riparian plants to “encroach into the river, interstitial riverbed habitats are covered with sedimentation, and a wide variety of bird species that capitalize on use of diverse flora of riparian canopies are no longer able to flourish in the area once the diversity of plant species are simplified” (Mulvaney 2009, 315-337). Due to habitat loss caused by the dewatering of at least 35% of the state’s formerly perennial rivers and other factors, Arizona native fish are some of the most imperiled animal species in North America (Turner and List 2007, 737-748).

Every stream is shaped by its watershed. A watershed is the area of land that drains to a specific water source. The watershed context means that everyone is upstream or downstream of a river. Actions (such as building roads, disposing of chemicals, etc.) at upstream points in a watershed can affect water quality and how water moves across the landscape.

All streams and rivers function within the hydrologic cycle (Figure 2). Groundwater becomes part of surface water or springs through discharge, and surface water may join groundwater through recharge. Flowing surface water is a combination of groundwater “springing” from the earth and precipitation collected at the lowest point in the basin as runoff. Precipitation ends up in groundwater, streams, plants and animals. Groundwater is stored in aquifers, which are underground storage areas where water moves in the pore space between soil, sand, and rocks. Water within an aquifer may be moving constantly.

Figure 2. The Hydrologic Cycle (Source: Water Resources Research Center, 2010)



Riparian areas have been called “ribbons of life” because they are considered the most productive habitats in North America, despite covering only 113,000 hectares in Arizona (279,223 acres; 0.4% of Arizona’s total area), 40,750 hectares (100,248 acres) of which are along the Gila River (Zaimes 2007). In comparison to terrestrial uplands, riparian areas support a more productive and diverse vegetation assemblage and serve more ecological functions. They act as links between terrestrial upland and aquatic ecosystems.

Wildlife depends on these riparian areas, especially in arid regions, for foraging, nesting or cover during part of or for an entire life cycle. In Arizona, 80% of all vertebrates spend some portion of their life cycle in riparian areas; 70% of Arizona’s threatened and endangered vertebrates depend on riparian habitat (Zaimes 2007). Domestic livestock often rely on these areas for their high forage abundance and water supplies. Riparian areas are considered prime areas for recreational activities as well.

A perennial stream is one that has water flowing throughout the year, while an intermittent stream only contains water during a portion of the year, and an ephemeral stream only after a precipitation event. Understanding the extent of Arizona’s perennial and formerly perennial streams and riparian areas is important for assessing the state’s water needs. This is because many species have become threatened, endangered, or seen a reduction in habitat size as a direct result of Arizona’s agricultural, industrial, business, and residential water use. The movement of water through the hydrologic cycle is also influenced by natural and artificial streams and lakes, rerouting of waterways to generate power, and other alterations to the natural landscape. Arizona has seen a large number of these environmental changes. The current status of perennial, formerly perennial, intermittent and ephemeral streams within the state highlights this impact.

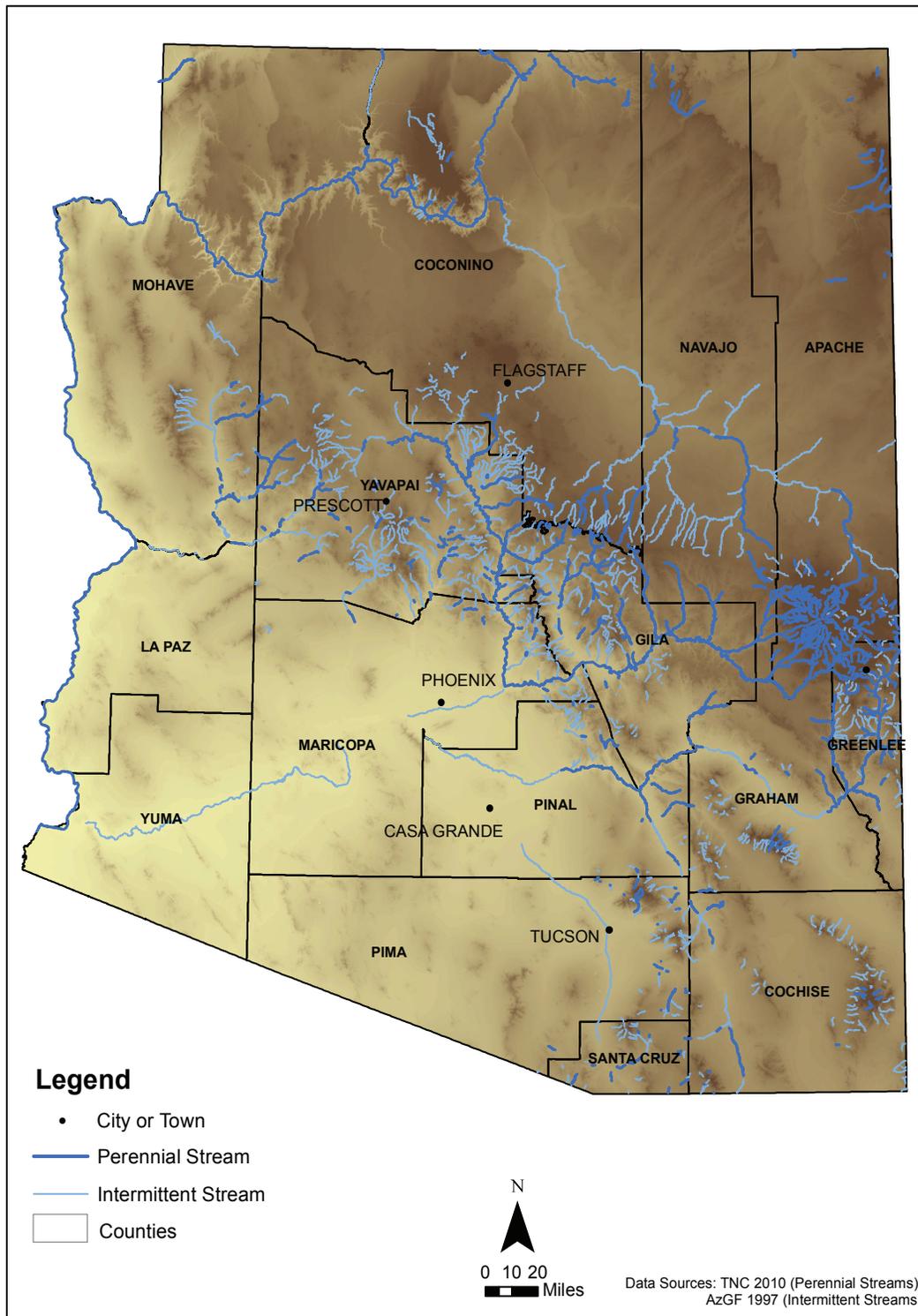
Unfortunately, Arizona ranks “first among US states in the proportion of native freshwater species at risk of extinction” (Turner and List 2007, 737-748). Though many streams in Arizona are dry some or all of the year, perennial flows occur much of around the state (Figure 3). Locations of intermittent and perennial flows indicate opportunities for preservation and conservation, while formerly perennial flows may indicate opportunities for restoration.



Beaver Creek, Sedona, AZ. Photo Credit: Brittany Choate

Humans have the capacity to drastically impact those five elements of a riparian or stream ecosystem previously discussed. Managing riparian or aquatic habitats often involves preserving and managing patches of habitat that can be identified on a map or spatial representation. Maps also can be useful for identifying areas that need quantification or further study. But the reality is that these systems are dynamic, and habitat patches are being destroyed and created constantly. To be managed well, they require more information than just the location and distribution of riparian habitat. To manage for the long-term, we need a systems perspective. We need to think about more than just the trees and the flowing water, to look more deeply at all the related elements that make these systems function and thrive. These systems must be understood as a whole, shaped by disturbance processes and with many interconnected parts.

Figure 3. Location of Perennial Streams in Arizona



II. SUMMARY OF ARIZONA STUDIES OF ENVIRONMENTAL WATER NEEDS

OVERVIEW

We compiled an extensive list of environmental water needs studies through a literature search, interviews with experts, and the assistance of an advisory committee. Studies were categorized based on their geographic extent, study focus, and study type. Additional categories were added to further separate approaches and results. Information about environmental water needs came from many sources – studies done for the express purpose of answering questions about flow needs as well as studies performed for other purposes that have minimal reference to environmental water needs.

Arizona is comprised of 17 river basins, four of which lie mostly outside the state and are therefore not discussed. The four excluded basins are the Rio Asuncion, Rio Bavispe, Rio Sonoyta, and Lower San Juan River, which did not have any studies of environmental water needs. The river basin boundaries are based on the HUC-6 (Hydrologic Unit Code) system (Figure 4). The

general location of studies across the state is indicated according to the HUC-6 river basin. Specific stream segments are also delineated where sufficient information was available. Maps of study locations represent the data collection sites or focus area of analyses. Experimental studies that were done ex situ (not on site) are characterized according to the study location they are intended to inform. If they are not intended to inform any specific location, they are categorized according to the distribution of the species they are studying.

In Arizona, 93 studies provide some indication of the natural environment’s water requirement (Figure 5). Not surprisingly, all of the studies demonstrate some connection between water availability and ecological health. Multi-chapter reports are counted according to individual chapters when each chapter represents a separate study. For the purpose of this assessment, we only reviewed studies that investigate water needs for riparian (river banks and terraces), aquatic (in-stream), and spring ecosystems. We will use the term “environmental water needs” to refer to both ecological flow

requirements and ecological responses to flow alteration. Some studies reviewed focus on the flows involved in moving sediment (or maintaining geomorphologic characteristics) important for river ecosystems. Unless these studies also contained information about environmental water needs for biota, they were not included in the inventory (e.g. newer and Wiele 2007; Wiele et al. 2009).

Figure 4. Arizona River Basins

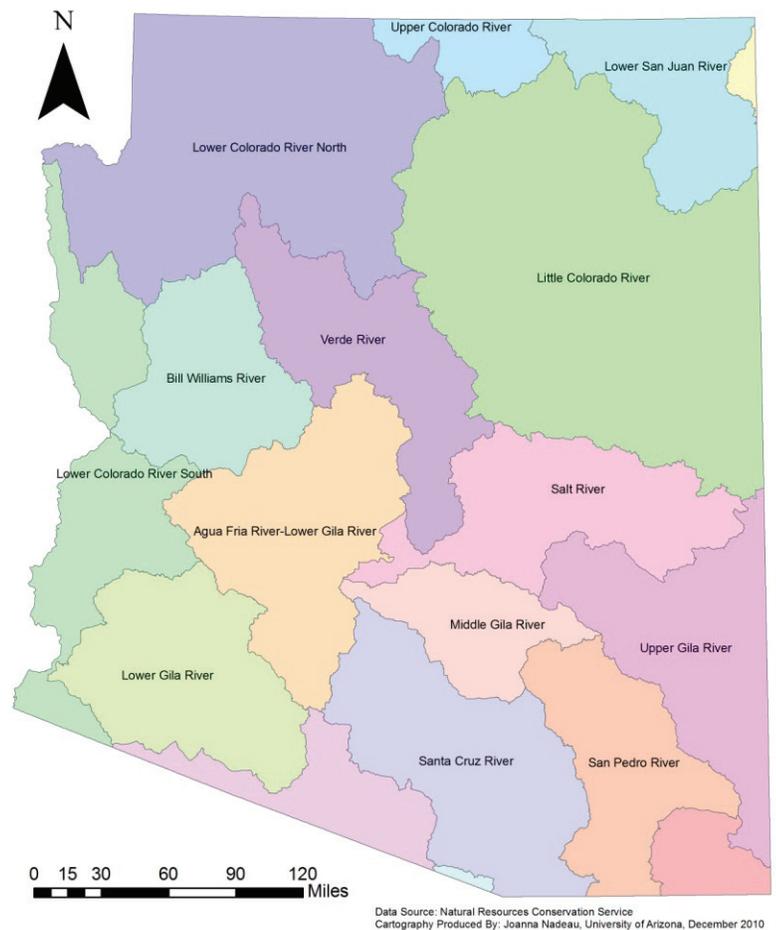
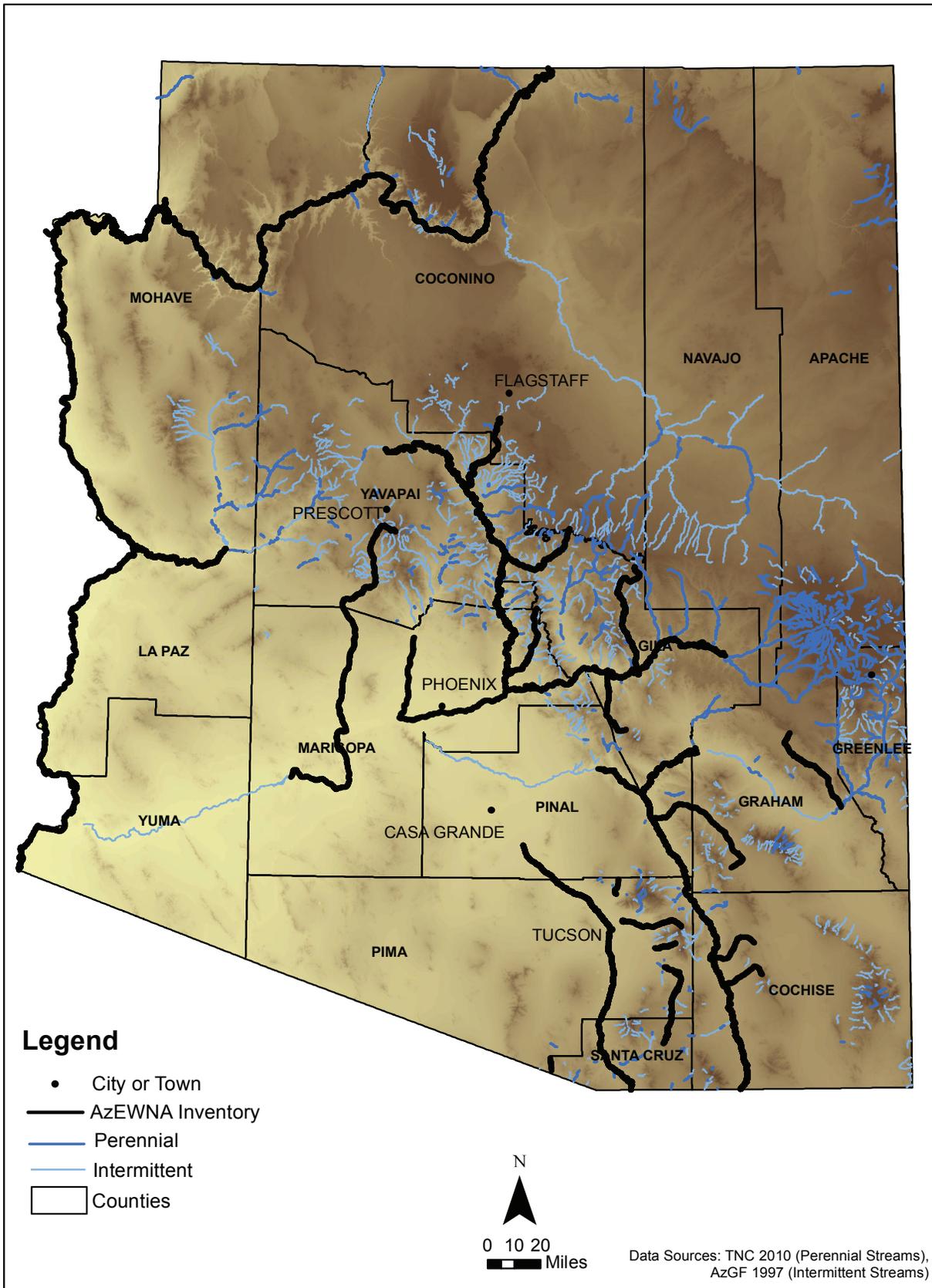


Figure 5. Extent of Inventory Studies



QUALITATIVE ANALYSIS - WHAT KINDS OF THINGS DID THEY STUDY?

Each study in the inventory represents a single field experiment, modeling experiment, or a review/synthesis paper of multiple studies. Review or synthesis papers summarize findings from many field studies on a given topic, while single studies tend to focus on identifying water needs of one or more species or hydrological elements. Review or synthesis studies are helpful in identifying and summarizing groups of single studies. More than half of the studies in our inventory are single studies (Table 1).

Table 1. Arizona Studies of Environmental Water Needs

River Basin	Multiple Study Synthesis	Review of Multiple Studies	Single Study
San Pedro	8	11	22
Bill Williams	6	4	4
Santa Cruz	6	5	11
Verde	6	1	8
Lower Colorado (N)	2	2	8
Upper Gila	1	0	4
Lower Colorado (S)	2	1	3
Lower Gila	0	0	3
Agua Fria-Lower Gila	0	0	3
Salt	1	0	1
Middle Gila	0	0	1
Upper Colorado	1	0	0
Little Colorado	0	0	1
Total	25	17	51

Research about environmental water needs can be done in different ways. First, researchers may study the flow needed to maintain a healthy aquatic ecosystem, a healthy riparian area, or both. Next, they might rely on the historical flow patterns to define flow needs or develop relationships to demonstrate the ecological components supported by a natural flow regime. Some studies collect reams of field data, perform sophisticated statistical analyses, and use spatial mapping to study flow-ecology relationships. Others rely on expert analysis of published literature to identify ecologically important components of flow regimes. Alternately, a handful of studies quantified the social or economic value of riparian or river ecosystems, which could then be linked to the water needed to preserve those human-valued ecosystem elements. More detailed information about the methods used in Arizona environmental water needs studies is located in the companion Methodology Guidebook.

Riparian areas are known to be critical for many wildlife species and, geographically, have been studied extensively (Figure 6). In Arizona, the majority of e-flow research in our inventory (64 of 93 studies) examines the water needs of riparian ecosystem elements only (i.e. they did not consider aquatic species’ water needs). Water requirements for both riparian and aquatic species are studied jointly in a handful of streams (Figure 7). Only twelve studies address aquatic water needs by themselves (Figure 8).

Statewide, the water needs of some taxonomic groups have been more frequently studied than others (Figure 9). A taxonomic group is a group of species that are related and have common characteristics that differentiate them from other such groups. Riparian trees (64) and shrubs (53) have been the most widely studied taxa for water needs. Mammals, amphibians, and reptiles have been studied the least often (15, 12, and 11 studies, respectively) and only in the Santa Cruz and Bill Williams River basins. Most papers (66) report on the water needs of multiple species. Twenty-five papers address the water needs of multiple plant and animal species. More than half of the papers only address plant species.

Figure 6. Extent of Studies of Riparian Water Needs

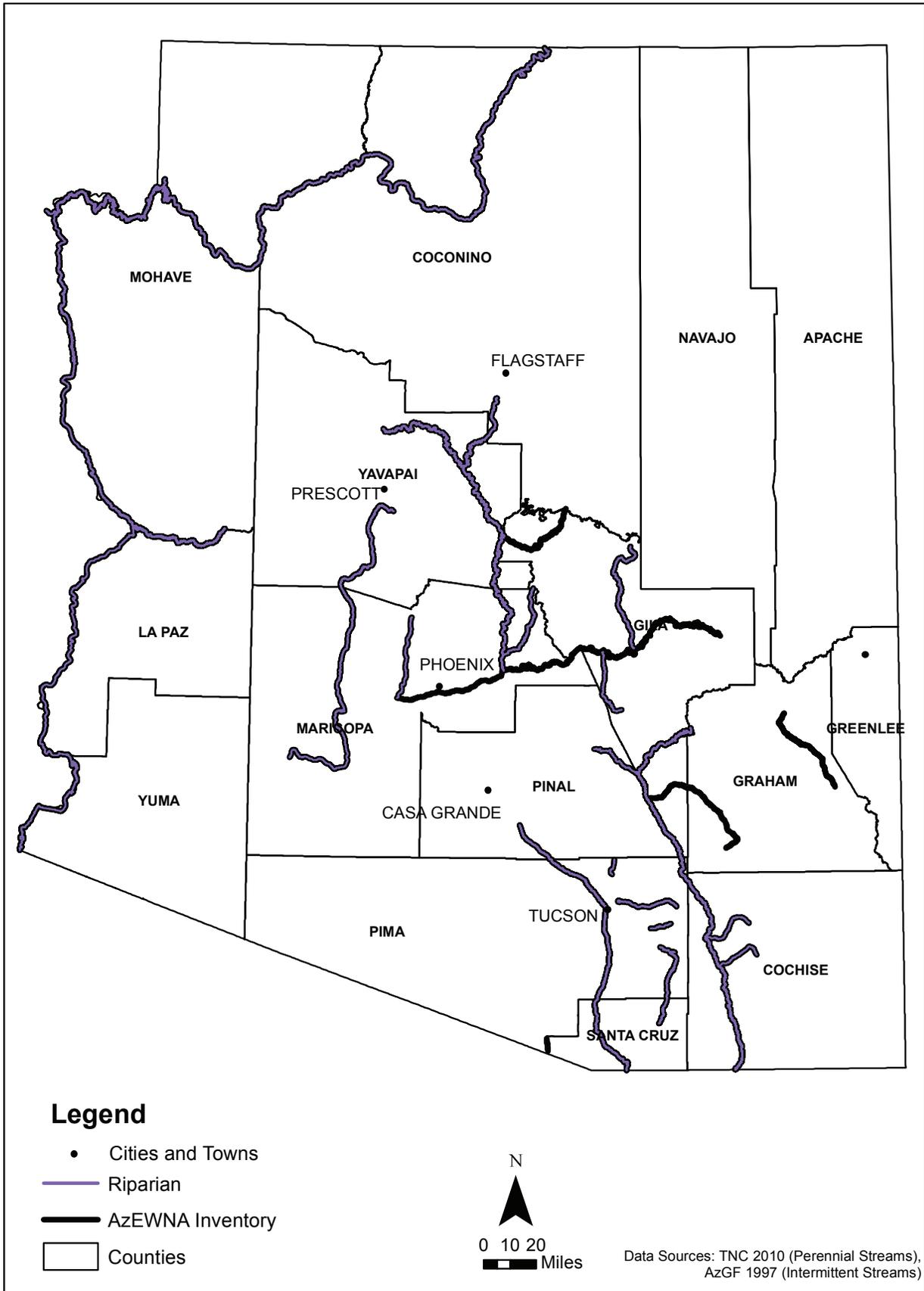


Figure 7. Extent of Riparian and Aquatic Studies

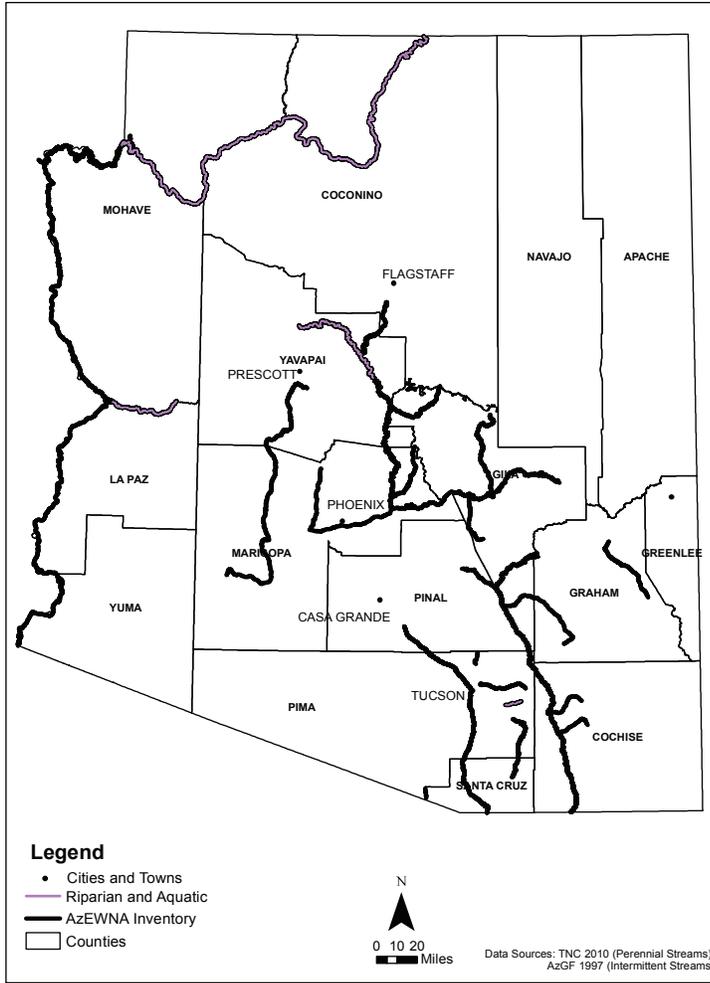


Figure 8. Extent of Aquatic Studies

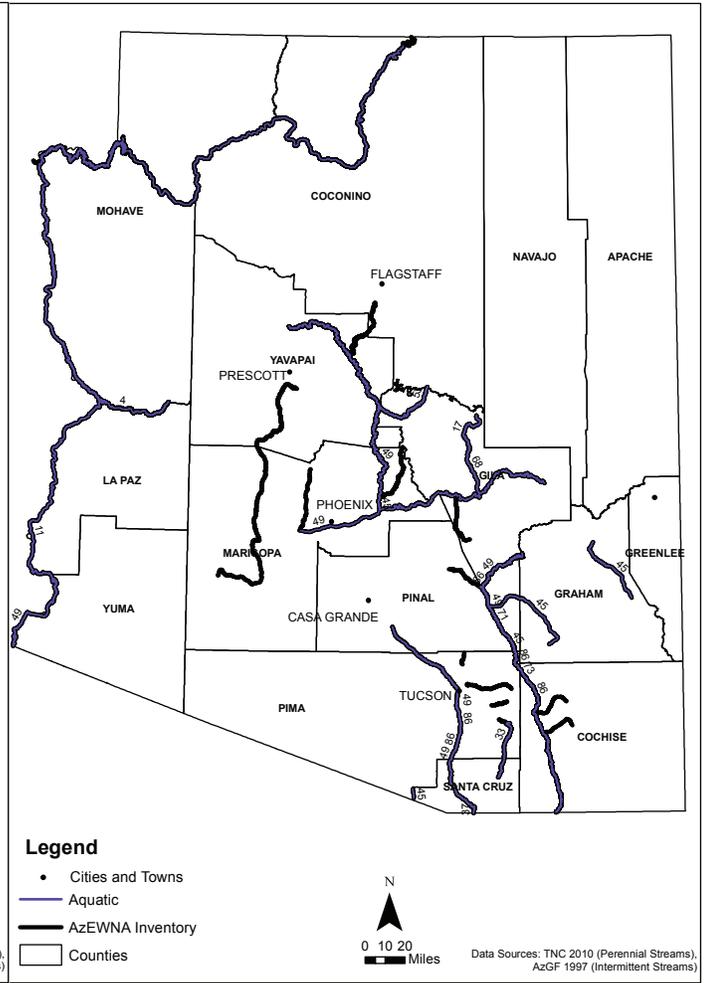
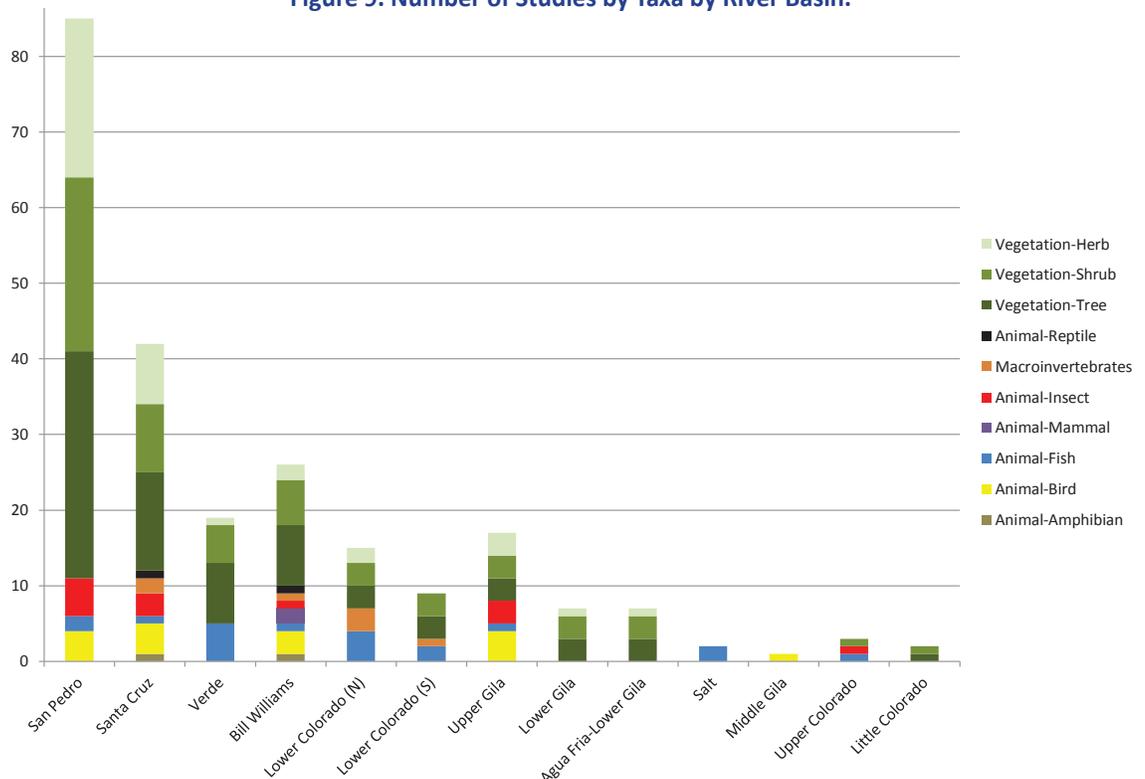


Figure 9. Number of Studies by Taxa by River Basin.



METHODS USED

Methods for defining environmental water needs differ in terms of what information they use to represent relationships between living things and components of water flow. Studies are needed that describe and quantify ecological flow needs or flow responses in order to place environmental water needs on an even playing field with other uses. Our inventory does include qualitative (descriptive) studies and valuation studies, which offer other insights about environmental water needs. However, we concentrate most of this analysis on studies that use quantitative e-flow methods to describe environmental water needs (i.e. those that produce numeric results). Eighteen of the inventoried studies provide little description of methods used therein; though those may have used some additional methods, they are not reported here.

Most studies (70) in our inventory quantify environmental water needs in some way. At least one quantitative study exists in every river basin covered by our inventory. Multiple study synthesis papers and single studies were more likely to provide quantitative results about environmental water needs than review papers.

The hydrological context provides a first cut in distinguishing methods, and therefore, studies. Researchers may focus a study on the water needed to maintain a healthy aquatic ecosystem, a healthy riparian area, or both (Table 2). Worldwide, methods for investigating aquatic ecosystems (or aquatic methods) are applied most frequently

Table 2. Method Classification

Qualitative Methods	
Aquatic	Riparian
Hydrological index	Hydrological event models
Hydraulic rating	Water budget/Evapotranspiration
Habitat Simulation	Water Source
Biological response to flow correlation	Eco-flow response curves Biological event models
Holistic	

in e-flows studies (Tharme 2003, 397-441). However, most studies in Arizona use riparian methods to quantify environmental water needs. Only 18 studies use aquatic methods, and three use holistic approaches. Holistic methods consider the flow needs of physical and biological elements across both aquatic and riparian areas.

Some aquatic methods can be adapted to study riparian taxa. For example, a hydraulic rating method called the Hydrologic Engineering Centers River Analysis System

(HEC-RAS) was used to relate riparian plant responses to floodplain inundation patterns and groundwater availability on the San Pedro, Santa Cruz, and Bill Williams Rivers (Leenhouts, Stromberg, and Scott 2006, 154; Briggs, Magirl, and Hess 2007, 79; Hautzinger, Hickey, and Walker 2008, 28-30). Most methods commonly applied to riparian areas have not been used to study aquatic taxa in Arizona.

The majority of studies employing riparian methods use ecological-flow response curves portraying species level-processes (29 of 52; Table 3). Ecological-flow response curves portraying community level-processes and evapotranspiration studies are the next most commonly used riparian methods. Similarly, the method most commonly applied in aquatic studies is correlation of flow attributes (e.g. magnitude and timing) with biological responses. A look at Arizona e-flows methods proves that e-flows science is evolving rapidly. Sixteen studies included in this assessment offer variations on previously established methods. Thirty-four Arizona studies use multiple method classes (Methodology Guidebook: Table 1) to describe environmental water needs.

When designing a study, ecologists or hydrologists must weigh the benefits of conducting controlled experiments on their study subject since these tend to be less realistic. On the other hand, since factors affecting the natural environment are challenging to decouple, controlled experiments offer clarity about relationships between variables. Only seven studies in the inventory were performed all or in part through controlled experiments (five of those were performed off site). Just over half (54) of the studies in our inventory take an observational approach to understanding environmental water needs. Relationships between water and living things can be observed at a point in time (cross-sectional approach) or at a series of data points (longitudinal approach). Twenty-nine studies take a cross-sectional look at water needs; 26 do longitudinal analysis; one does both.

Table 3. Number of Studies by Method

Riparian Methods Class - 52 studies total								
Eco-flow response curves - Species-level	Eco-flow response curves - Community level	Water budget/ET studies	Eco-flow response curves - Physiological	Hydrological event Models - IHA/RVA	Biological event Models - Other	Water source studies - Use of isotopes	Water source studies - Spatial contrasts	Biological event Models - HEC-EFM
29	22	17	7	4	4	2	1	1
Aquatic Methods class - 18 studies total								
Biological response to flow correlation (flow attributes)	Hydraulic rating - 1-d HEC-RAS	Habitat simulation - other	Biological response to flow correlation (quality)	Hydraulic rating - other	Hydraulic rating - 2-dimensional	Narrative justification	Hydrologic - Great Plains method	Habitat simulation - IFIM
6	4	4	4	4	3	2	1	1
Holistic Methods Class - 3 studies total								
			Holistic - Building Block Methods	Holistic - Other				
			2	2				

In addition to or instead of experimental and observational methods, some researchers employ predictive models to study environmental water needs (16 studies). In most predictive studies, ecosystem components known to be important for subject species are considered under various flow alteration scenarios to identify likely biotic responses. Modeling scenarios may be useful where you cannot run actual flow experiments (Springer et al. 1999, 3621-3630).

E-Flow Methods At a Glance

Aquatic E-flow Methods

- **Hydrological Index** methods rely on hydrological data (naturalized or historical monthly or daily flow records) to make environmental flow recommendations.
- **Hydraulic rating** methods use changes in hydraulic variables as a surrogate for habitat factors thought to be important to biota.
- **Habitat simulation** methods analyze quantity and suitability of instream habitat for key species available under different flows to determine habitat-discharge curves.
- **Biological response** to flow correlation methods establish a relationship between biological data and a flow related variable (e.g. water quality or timing of flow).

Riparian E-flow Methods

- **Hydrological event** models depict natural flow regimes assumed to benefit ecological functions of riparian area.
- **Water budget/Evapotranspiration** studies are remote sensing studies of plant water use that predict water needs at landscape scales.
- **Water source** studies determine reliance of plants and animals on groundwater, surface water, etc.
- **Eco-flow** response curves depict quantitative relationships between a surface flow or groundwater variable and biological processes.
- **Biological event** models characterize flow pulses designed to mobilize sediments, initiate biological events and drive ecological processes.

Holistic E-flow Methods

- **Holistic methods** identify critical flow events for many or all major biological and physical components of the river system.

Both riparian and aquatic species rely on multiple components of the flow regime, and studying them concurrently provides a more robust picture of environmental flow needs. Forty-six of the seventy quantitative studies in our inventory investigate the relationship between multiple hydrological elements and environmental water needs. Ideally, all e-flows studies would take such a holistic look at the ecosystem. Perhaps because this is an emerging science, a holistic approach has not been applied often to study concerns about, for example, a certain species (e.g. an endangered species) that has fewer variables of interest to and under the control of managers.

Across the state, more studies describe the relationship between surface water and biological elements than describe the relationship between groundwater and biota, though this varies by river basin (Table 4). Three studies define flow needs using just hydrological components in the absence of quantitative data about biological responses, based on the assumption that a naturalized flow regime will provide what is important to biota.

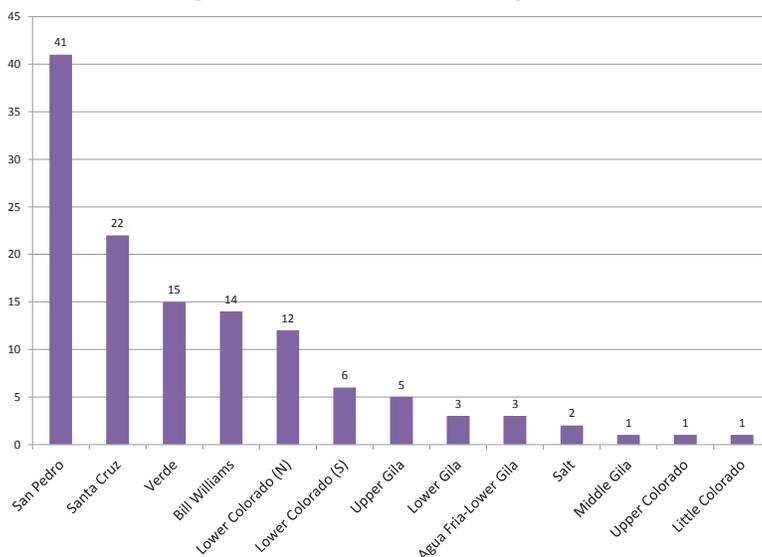
Table 4. Number of Studies by Basin Quantifying Ecological Relationships with Surface and Groundwater

River Basin	Surface Water	Groundwater
San Pedro	20	28
Santa Cruz	12	10
Verde	12	3
Bill Williams	8	4
Lower Colorado (N)	4	0
Upper Gila	5	3
Lower Colorado (S)	2	0
Lower Gila	1	3
Agua Fria-Lower Gila	1	3
Salt	3	0
Middle Gila	0	0
Upper Colorado	0	0
Little Colorado	0	0

SPATIAL ANALYSIS - WHERE WERE STUDIES DONE?

When defining environmental water needs, most studies (75 of 93) focus on a single river basin within Arizona. No studies consider water demands for the environment on a statewide scale. The remaining 18 studies relate to more than one river basin. Some basins have been the subject of intensive study, while others remain poorly

Figure 10. Number of Studies by Basin

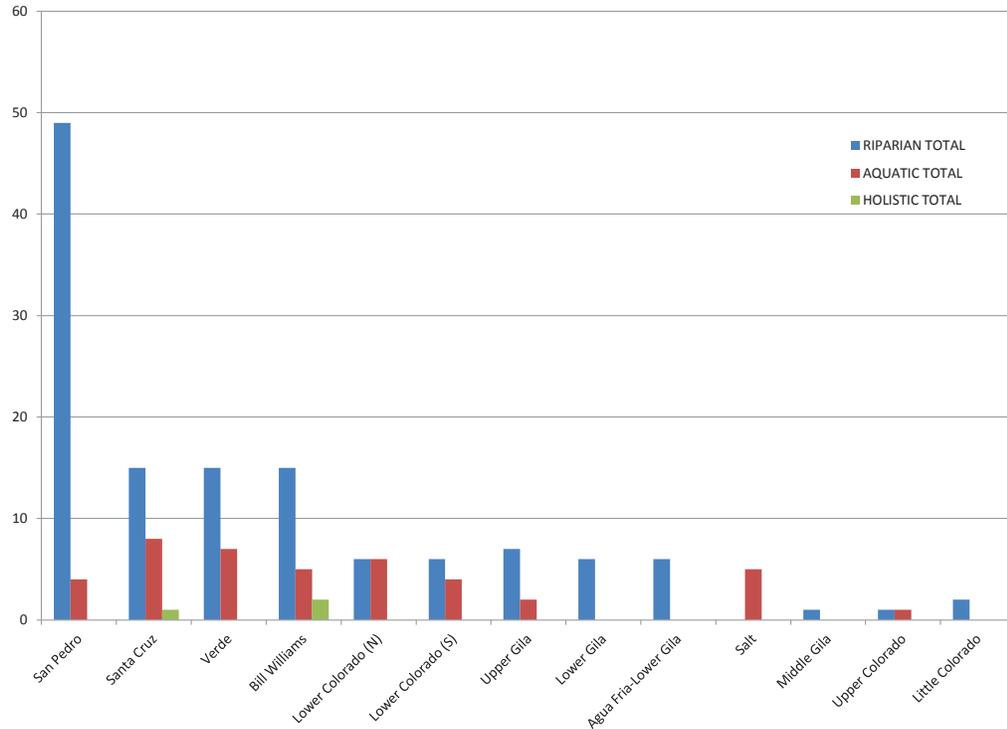


understood: 41 studies were done on the San Pedro River basin; few studies have been found for the Middle Gila, Upper and Little Colorado River basins (Figure 10). At least a portion of 12 studies were conducted in laboratory conditions off site (ex situ). Despite the fact that perennial streams occur across the state, many have not been studied extensively if at all. Most basins have fewer than 10 studies on any aspect of environmental water needs, providing a somewhat limited basis for inter-basin analysis. Also, knowing the water needs of just a few species, but not all, limits the water manager’s ability to ensure adequate flows to protect the whole ecosystem.

Riparian and aquatic water needs have been studied concurrently in the Bill Williams, Lower

Colorado (below Lees Ferry), Santa Cruz, Upper Colorado, and Verde River basins. Only on the Santa Cruz and Bill Williams Rivers have holistic methodologies been used (Figure 11). Most of the studies quantifying water quality needs (five of nine) were done on the Lower Colorado River. Other studies quantifying ecological responses to water quality have been conducted on the Verde River, the Bill Williams, the Santa Cruz, the Gila, the San Pedro, and the Salt River basins.

Figure 11. Number of Studies Using Method Types by Basin



FINDINGS OF STUDIES - WHAT DO WE KNOW?

Knowing what elements of environmental water needs have been studied only tells us so much; the real question is what they tell us about water needs.

Based on this inventory, more Arizona studies quantified ecological flow responses than flow needs (Table 5). Three studies synthesized quantitative information about both flow needs and flow responses. Review papers tended to focus on flow needs instead of flow responses. When more than one study presents the same findings in terms of water needs, those results are counted repeatedly (once for every mention). Thus, summary tables show number of instances where findings are reported, and totals may be greater than the number of studies in the inventory.

A quarter (11 of 40) of quantitative flow needs studies considered aquatic species, while most (36) described riparian species' flow needs. One way to determine a flow need is by identifying the point at which an individual will die, or a mortality threshold. Another type of threshold is when the composition of a community shifts to a new dominant type (Lite and Stromberg 2005b, 153-167). Flow needs may also be defined in the context of management goals, such as preserving a historical flow regime.

Ecological flow responses differ from flow needs because they provide insight into how ecosystems react in response to changes in water availability. Twelve studies describe aquatic species' responses to flow elements; 43 studies address riparian species' flow responses. Researchers have studied species survivorship in response to hydrological changes such as groundwater depth and surface flow permanence (perennial vs. intermittent).

Table 5. Number of Studies with Quantitative Findings by Basin

River Basin	Quantitative Findings	Flow Need	Flow Response
San Pedro	35	23	23
Santa Cruz	15	9	10
Verde	13	8	10
Bill Williams	9	5	7
Lower Colorado (N)	8	4	7
Upper Gila	5	2	5
Lower Colorado (S)	5	2	5
Lower Gila	3	1	3
Agua Fria-Lower Gila	3	1	3
Salt	2	2	2
Middle Gila	1	0	2
Upper Colorado	1	0	1
Little Colorado	1	0	1
Total	70	40	51

Other metrics are used to study ecological flow responses including measurements at the community level (e.g. species diversity), species population level (e.g. abundance or reproductive success), and even at the level of individual physiology (e.g. growth or vigor). These ecological metrics can be measured against the basic five flow components: magnitude, frequency, duration, timing, and rate of change of flow. Flow components studied for ecological importance include surface flow and groundwater. In several cases, flow needs were determined by looking at a species’ flow responses.

Studies in the inventory provide quantitative information about the flow needs and flow responses of many riparian and aquatic taxa (Table 6). The study inventory database includes information on the page numbers where quantitative data can be found for each study. This does not mean that studies have been done on every aquatic and riparian species in Arizona. But it does indicate that some taxa are studied more often than others – plants, fish, and birds top the list. Flow responses for each taxonomic group are more often quantified than their flow needs, with the exception of amphibians, reptiles, and fish. In 51 instances, both flow responses and flow needs have been quantified for a given taxonomic group. Again, plants top the list (15, 12, and 9 respectively) in number of studies that quantify both flow needs and flow responses, with fish following (five).

Quantitative information about the flow needs of plants and fish is summarized in the next section. Additional detail about quantitative results is available in the studies themselves, referenced in Appendix B.

Table 6. Number of Studies Quantifying Flow Needs and Flow Responses by Taxa

	Flow Need (FN)	Flow Response (FR)	Both FN and FR	Total # Studies
Animal-Amphibian	2	1	1	2
Animal-Bird	5	7	3	9
Animal-Fish	9	8	5	12
Animal-Mammal	1	1	0	2
Animal-Insect	3	6	2	7
Invertebrates	3	6	3	6
Animal-Reptile	2	1	1	2
Vegetation-Tree	31	36	15	52
Vegetation-Shrub	21	28	12	37
Vegetation-Herb	17	18	9	26

WATER NEEDS OF PLANTS

Researchers have most extensively studied the water needs of Arizona’s riparian plants, quantifying plant water use, depth to water limits, and needed flood events. Water is a critical element in plant metabolism (or energy production process). Plants produce energy through photosynthesis, and their rate of water use in this process is measured as transpiration rates. Evapotranspiration has been measured for a variety of plant communities, such as cottonwood-willow, mesquite forest, and others (Table 7). Evapotranspiration rates for these communities can range significantly, especially since data comes from multiple river basins. Without access to water needed for photosynthesis vegetation health suffers, and eventually plants cannot survive.

Table 7. Evapotranspiration Rates for Plant Communities

Plant Community	Annual ET Range (mm/yr)	Study Author
Cottonwood-Willow	410-2000	ADWR 2005/Springer et al 1999
Grassland	643*	Scott et al 2008a
Mesquite Forest	380-1046	Williams 2009/Nagler et al 2005
Mesquite Shrub	157-486	Williams 2009/Scott et al 2008
Mixed Forest	410-727	ADWR 2005/Scott et al 2008
Saltcedar	375-750	ADWR 2005/Nagler et al 2005
Saltcedar/Native Trees	640*	Nagler et al 2005
Scrub/Mixed Deciduous	335*	ADWR 2005
Shrubland	661*	Scott et al 2008

*Only one value reported

Plants retrieve this water from the ground, when it is available. Groundwater availability is basically determined by the depth of the water table below the vegetation, in addition to soil characteristics. For the San Pedro River, estimates of maximum depth to groundwater for cottonwood-willow riparian plant communities range between one (young cottonwood) and six meters (Table 8; see table for references). For mesquite woodlands, maximum depth ranges between six (maximum growth) and fourteen meters (extinction depth).

Table 8. Depth to Groundwater (Range) for Plant Species in San Pedro River

Species	Minimum Depth (m)	Maximum Depth (m)	Notes	Study Author
Bullrush (Scirpus)		0.25		Shafroth&Beauchamp 2006
Cattail	0.00	0.30		Pima County 2009a
Cottonwood (mature)	1.00	3.00		Pima County 2009a
Cottonwood (young)	0.30	1.00		Pima County 2009a
Cottonwood (Fremont)	4.00	5.00		Lite and Stromberg 2005b
Cottonwood (Fremont)		4--6		Stromberg et al 2009a
Deer Grass	0.30	1.00		Pima County 2009a
Horsetail	0.00	0.30		Pima County 2009a
Mesquite		14.00	Extinction Depth	Leake et al 2008
Mesquite	4.00	8.00		Pima County 2009a
Mesquite	5.00	6.00	Maximum Growth	Shafroth&Beauchamp 2006
Mesquite	5.00	10.00	Maximum Growth	Stromberg et al 2009b
Sacaton	3.00	4.00		Pima County 2009a
Sacaton	3.00	4.00		Stromberg et al 2009b
Riparian Woodland		6.00	Extinction Depth	Leake et al 2008
Willow (Seep)	1.00	3.00		Pima County 2009a
Willow (Gooding's)	1.00	3.00		Pima County 2009a
Willow (Gooding's)		4--6		Stromberg et al 2009b
Willow (Gooding's)	4.00	5.00		Lite and Stromberg 2005b

1 m³/s=
22,800,000 gallons/day

1 ft³/s (cfs)=
646.272 gallons/day

AF=acre-feet

1 m³/s=
0.000811 AFs

1ft³/s (cfs)=
0.0000229 AF/s

Although there is an obvious connection between groundwater and riparian vegetation, surface flow elements such as flood frequency and flow permanence are also important to riparian vegetation (Briggs 2008, 106; Hautzinger et al. 2006, 71; Leenhouts, Stromberg, and Scott 2006, 154; Stromberg 2001b, 227--239). A prominent example of this is the Kearsley (1999) study on the Colorado River, which proved the effect of a high flow event on riparian vegetation through scouring.

These and many other studies have shown that both groundwater and surface water are needed for riparian plants, which are in turn critical for riparian ecosystem health. Several Arizona studies also demonstrate an important connection between water available to riparian vegetation and the health of insects and birds – one on the San Pedro and one that covered the San Pedro, Santa Cruz, and Upper Gila (Kirkpatrick et al. 2007; Sabo et al. 2008).

WATER NEEDS OF FISH

Surface flows needed for Arizona’s native fish vary across geography and according to river or stream size, as well as by species (Table 9). Arizona’s environmental water needs studies prescribe a wide mix of flows needed for fish in the Bill Williams River, Colorado River, and Cherry Creek. Recommended flows for the Bill Williams River and Cherry Creek range between 0.14 and 2.3 m³/s (4.94 and 81.2 ft³/s); recommended Colorado River flows are 505 m³/s (17833 ft³/s). Each study characterizes flow needs slightly differently: Hautzinger et al. (2006) prescribe different seasonal baseflows for dry years and wet years along the Bill Williams; two Colorado River papers provide average historical flows as a guide to flow needs; and a study in the Salt River basin characterized flows needed to protect native fish habitat (Waddle and Bovee 2009, 161).

Just as fish species in the same river reach can differ in their flow needs, fish of different ages can also require different flows. For the Verde River, Stevens, Turner, and Supplee (2008) identified flow velocity (speed) needed to maintain native habitat for the longfin dace, speckled dace, and spikedace as 0.3, 0.4, and 0.11-0.31 m/s

Table 9. Flow Volumes Needed for Fish

River Basin	Fish Species	Flow Needed (cfs)	Flow Detail	Study Author
Bill Williams	Aquatic Group	5.3	Dry years, dry season baseflow requirements	Hautzinger et al. 2006
Bill Williams	Aquatic Group	20.1	Dry years, monsoon season baseflow requirements	Hautzinger et al. 2006
Bill Williams	Aquatic Group	49.4	Dry years, winter-spring baseflow requirements	Hautzinger et al. 2006
Bill Williams	Aquatic Group	9.9	Wet years, dry season baseflow requirements	Hautzinger et al. 2006
Bill Williams	Aquatic Group	49.4	Wet years, monsoon season baseflow requirements	Hautzinger et al. 2006
Bill Williams	Aquatic Group	81.2	Wet years, winter-spring baseflow requirements	Hautzinger et al. 2006
Colorado River	Many (e.g. roundtail chub, speckled dace)	17834.4	Average flow from 1912 to 1969	Schmidt et al 1998
Salt (Cherry Creek)	Longfin dace	3--30	Daily flow needed to retain 90% habitat	USGS, Waddle 2009
Salt (Cherry Creek)	Roundtail chub	5--25	Daily flow needed to retain 90% habitat	USGS, Waddle 2009
Salt (Cherry Creek)	Desert sucker	5--30	Daily flow needed to retain 90% habitat	USGS, Waddle 2009
Salt (Cherry Creek)	Speckled dace	10--40	Daily flow needed to retain 90% habitat	USGS, Waddle 2009
Salt (Cherry Creek)	Sonora sucker	25-50	Daily flow needed to retain 90% habitat	USGS, Waddle 2009

(0.98, 1.3, and 0.36-1.0 ft/s), respectively. For the Colorado River near Glen Canyon Dam, young humpback chub survive average water velocities of 0.12 m/s (0.39 ft/s), while older individuals are found most often at an average velocity of 0.32 m/s (1.04 ft/s) (U.S. Fish and Wildlife Service 2008). Achieving these flow velocities in water management requires translating flow velocities (m/s or f/s) to flow volume (m³/s or cfs) for each stream based on stream morphology or shape.

One of the other elements of flow that can affect ecosystem functioning is water quality. Nine studies were found that quantitatively discussed water quality requirements or responses of ecological elements in Arizona. Most of these (six) focused on water temperature specifically. At least two of these papers found that native fish have relatively wide temperature tolerance ranges with specific limits. Schmidt et al. (1998) indicate that native fish in the Colorado River need a minimum temperature of 16 °C for spawning, and Carveth et al. (2006) found that native fish will die at temperatures above 36-42 °C, depending on the species.

OTHER STUDY TYPES

Valuation studies are separated out for analysis because none connect valued elements of the ecosystem to the flows required to preserve those elements. Thus, while these studies indicate the social value of ecosystem elements, including instream flows and healthy riparian habitat, they do not prescribe water needed to sustain these values. We found 10 studies quantifying the economic or social value of rivers or riparian areas. Valuation studies were done on the San Pedro, Santa Cruz, Verde, and Lower Colorado (Lees Ferry) Rivers.

Where valuation was directly tied to environmental attributes, the study tended to value riparian areas. One of these studies considered the direct use values of instream flows while another used an extensive ecosystem services rubric to distinguish how individuals surveyed valued the river (West, Smith, and Auberle 2009, 9; Marcus 2009, 12). Four studies used real estate indices to investigate the economic value of riparian corridors, and another four studies determined the contribution of ecotourism to local economies.

Qualitative descriptions of environmental water needs can help identify key ecological relationships to flow elements. Furthermore, knowing the location of important, water-adapted species can aid managers in avoiding impacts. Studies describing eco-flow relationships may be useful in educating the public and decision makers about the basic functioning of these ecosystems. Those studies that depict eco-flow relationships using charts and curves are most able to indicate the direction of response a given species would have to flow alteration.

FINDINGS BY BASIN

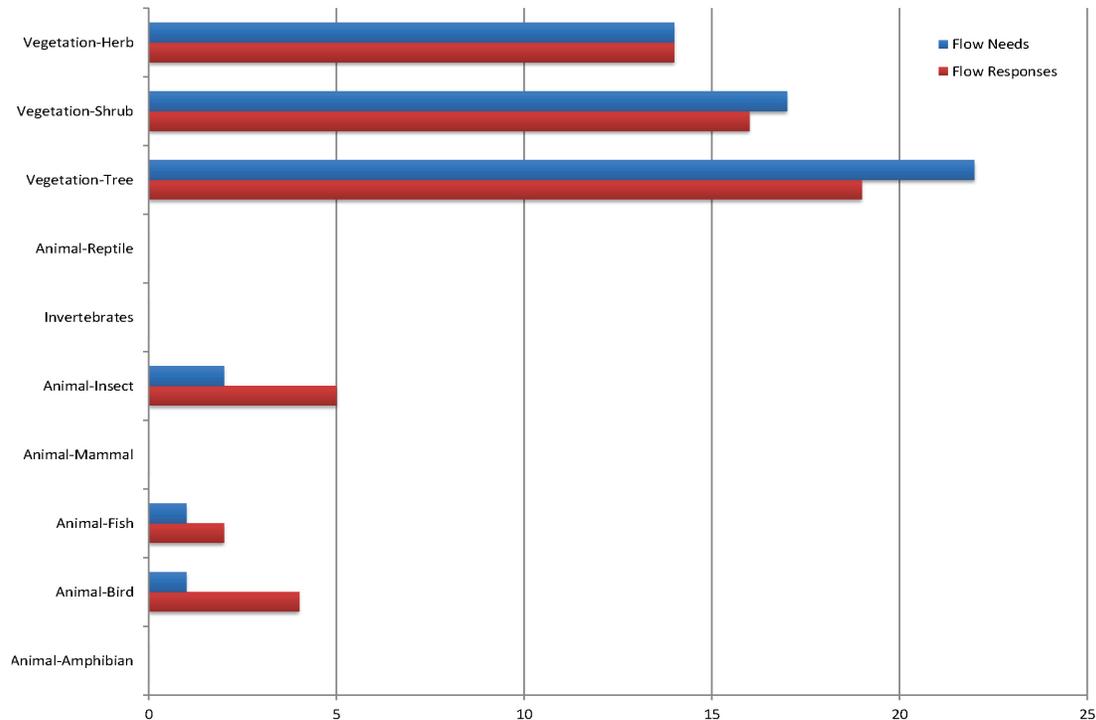
Most studies done in Arizona on environmental water needs focus on a single river basin. Those interested in a particular basin can refer to this summary of the inventory that is broken out by basin. For a comprehensive list of surveyed studies by river basin, see Appendix B.

The most studies of any type (multiple-study synthesis, review of studies, or single studies) have been done in the **San Pedro River** basin--41 in all (Figure 10; Table 1). Furthermore, the water needs of rivers and riparian areas in the San Pedro River basin have been quantified by the largest number of studies of any basin in the inventory (36; Table 5). The level of study in this basin can be attributed to the existence of the Upper San Pedro Partnership (USPP). The USPP was formed in 1998 to address the reliance of humans and the Riparian National Conservation Area on the same, diminishing water sources.

Quantitative studies of the San Pedro River basin and its riparian ecosystems focus in equal measure on flow needs (23) and flow responses (24). However, almost all studies in this basin are directed at understanding riparian water needs, with only three studies considering the water needs of aquatic taxa (Figure 9, Page 16). No studies in the San Pedro River have attempted to describe environmental water needs of both riparian and aquatic elements concurrently, and accordingly, no studies in the San Pedro basin have used holistic e-flows methods (Figure 11, Page 20).

In the San Pedro River basin, researchers concentrated the most on discerning the flow needs of trees (22 studies) and have done no studies on the water needs of reptiles, amphibians, mammals, or aquatic invertebrates (Figure 12). Slightly more is known about the flow responses of fish, birds, and insects in this basin than their flow needs, though these taxa are studied much less than plant species in general.

Figure 12. Number of Studies Quantifying Flow Needs and Flow Responses by Taxa in the San Pedro River Basin



Thirteen studies of the San Pedro River basin relate groundwater to ecological function, and thirteen relate the presence of surface flow to biota. Most of the studies that analyze the effect of surface flow also consider groundwater and its effect on biotic metrics. Four studies from the San Pedro link floods to critical ecological elements. Most of the San Pedro studies concerned with vegetative water needs link groundwater availability with maintaining riparian vegetation (see Table 8). One important finding from this basin is how the rate of change of hydrological variables matters to reproduction: if groundwater depth declines at a rate of more than one to four cm per day, cottonwood seedlings may not survive (Lite and Stromberg 2005, 153-167).

The prevalence of studies on plant water needs has not led to agreement on what exactly those needs are. For example, estimates for one section of the San Pedro River in terms of 2003 riparian vegetation groundwater use (determined by evapotranspiration) range from 8,130,000 to 11,112,000 m³/yr (6,591 AF/yr to 9,009 AF/yr) (Williams and Scott 2009, 37-56). On a slightly smaller, more northern section of the River studied by ADWR, riparian vegetation is estimated to use 7,544,568 m³/yr (6116.39 AF/yr; ADWR 2005). Similarly, Leenhouts et al. (2006) estimates total riparian evapotranspiration in different years, and for a slightly larger section of the same river, ranging from 9,498,000 to 14,867,000 m³/yr (7,700 AF/yr to 12,053 AF/yr). This discrepancy may arise in part because the estimates are based on assumptions about evaporation rates of riparian plants and estimates of land cover, both of which can vary greatly. Despite this, they at least provide a general sense that riparian vegetation on the San Pedro River uses around 10,000,000 m³/yr (8,100 AF/yr) of groundwater.

1 ft³/s (cfs)=
724 AF/year

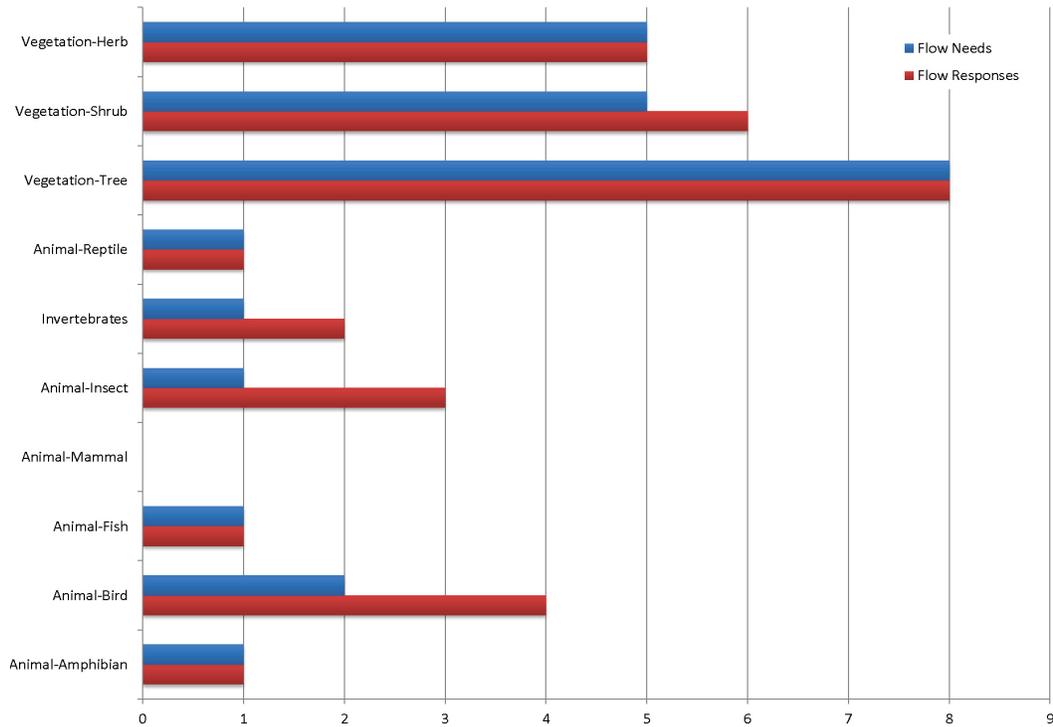
Leenhouts et al. (2006) provides the most extensive synthesis of the knowledge about riparian vegetation water use along the San Pedro River. Using the status and variability of hydrologic factors within the riparian system, the authors relate spatial and temporal aspects of riparian condition to the hydrologic variables. Then, they derive

groundwater use rates to determine total riparian groundwater use by species within the San Pedro National Conservation Area (SPRNCA). While the paper includes brief summaries of values of streamflow and riparian bird habitat, its major assertion is that vegetation characteristics of condition classes can be used to predict vegetation changes in response to changes in flow.

The next most studied river basin is the **Santa Cruz River** basin with 22 studies (Figure 10; Table 1). Half the studies conducted on the Santa Cruz River are single studies, a quarter are reviews, and the remaining are multiple study syntheses. The flow needs and flow responses of the Santa Cruz River have been quantified by similar numbers of studies (nine and ten respectively; Table 5). Studies of the Santa Cruz basin tend to focus on riparian water needs alone, with only four studies considering the water needs of aquatic taxa, and one study of riparian and aquatic water needs (Figure 9). One study in the Santa Cruz basin used holistic e-flows methods (Figure 11).

In the Santa Cruz River basin, researchers concentrated the most on learning about the flow needs and flow responses of trees (eight) and the least (no studies) on studying water needs of mammals (Figure 13). In the Santa Cruz River basin, flow needs are studied more frequently than flow responses. Shrub, herbaceous plants, and bird flow needs are studied almost as much as tree water needs.

Figure 13. Number of Studies Quantifying Flow Needs and Flow Responses by Taxa in the Santa Cruz River Basin



Nine studies in the Santa Cruz basin cited surface water flow magnitude as critical to ecosystem function; others indicated groundwater as a key hydrological element for ecosystem function (7 of 22). A study of Rincon Creek determined the required frequency of flooding for this tributary to the Santa Cruz River: native tree species recruitment requires flood events at a frequency of 10-15 years (Briggs 2008, 106). The same study also offers an example of the importance of both magnitude and timing of groundwater availability: riparian vegetation needs saturated soils within two meters of the soil surface in early summer (Briggs 2008, 106).

The most comprehensive study we found for the Santa Cruz River basin was completed on the middle reach of Rincon Creek for an instream flow water right application, which used some of Briggs (2008)'s analyses (NPS 2008). The National Park Service used a holistic method to determine flow needs for multiple elements of the creek ecosystem, resulting in recommendations of minimum daily discharge for each month of the year (Table 10). These

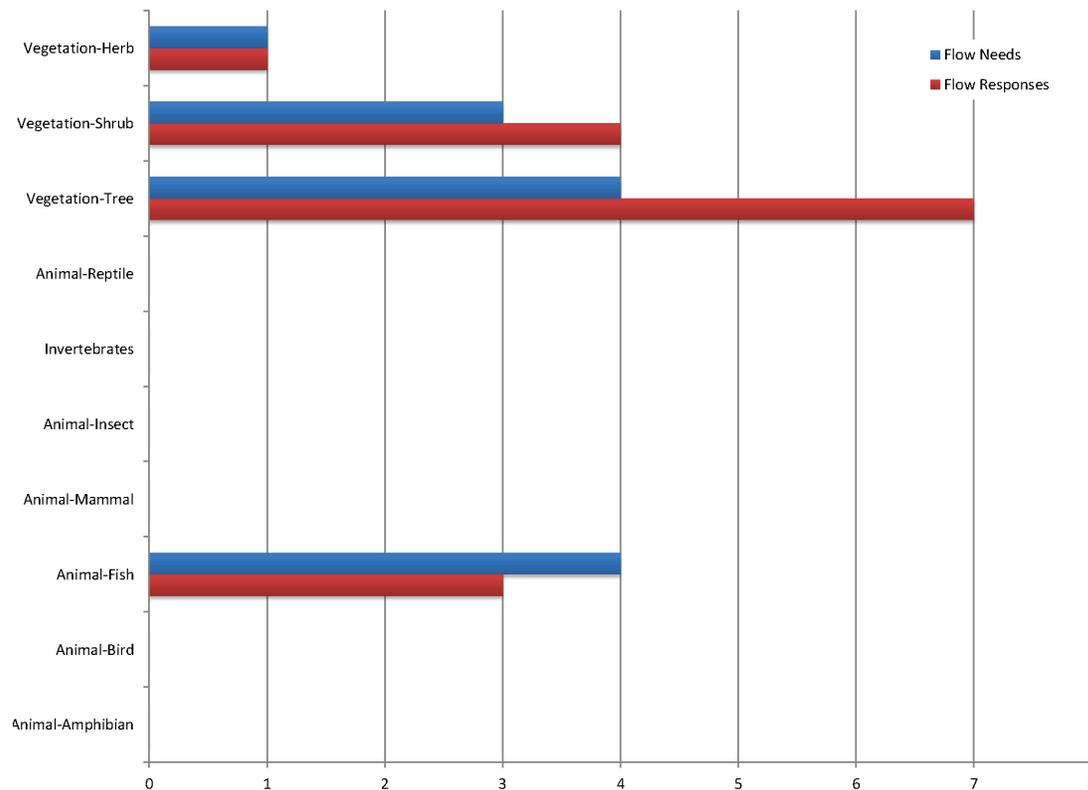
Table 10. Flow Recommendations for Rincon Creek

Month	Minimum Daily Discharge Recommended, ft ³ /s			Requested Minimum Daily Discharge, or the Natural Flow Whenever the Natural Flow is Less
	Aquatic Herptofauna	Aquatic Macroinvertebrates	Maintain Pool Levels	
Jan	-	1.50	0.20	1.50
Feb	-	1.50	0.20	1.50
Mar	1.40	3.00	0.20	3.00
Apr	0.23	2.00	0.20	2.00
May	0.09	1.00	0.20	1.00
Jun	-	0.50	0.20	0.50
Jul	-	-	0.20	0.20
Aug	1.00	1.00	0.20	1.00
Sep	1.00	1.00	0.20	1.00
Oct	-	0.50	0.20	0.50
Nov	-	0.50	0.20	0.50
Dec	-	0.50	0.20	0.50
Annual Volume A-ft	226	782	145	795

recommendations embody the assumption that the flow needs of mammals and birds will be met by water needs for aquatic species and bottomland plants.

In the **Verde River** basin, 15 studies on environmental water needs were found (Figure 10). The flow needs and flow responses of the Verde River have been studied relatively equally often (eight of ten studies respectively; Table 5). Twice as many studies focused on riparian water needs alone (11) as on aquatic water needs (five) in the Verde basin. Only two studies surveyed both riparian and aquatic water needs (Figure 9). Quantitative holistic

Figure 14. Number of Studies Quantifying Flow Needs and Flow Responses by Taxa in the Verde River Basin



methods were not used in the Verde River basin (Figure 11).

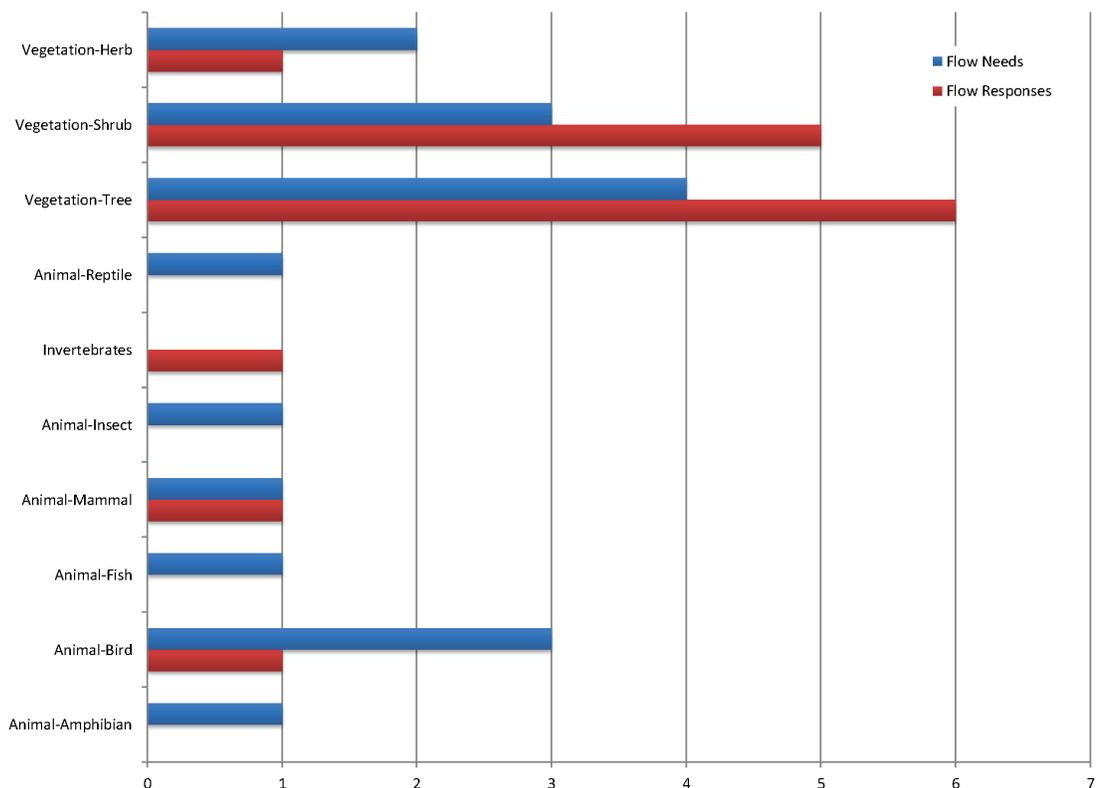
Quantitative studies from the Verde River basin have looked at the flow needs and flow responses of fish and tree, shrub, and herbaceous plant species (Figure 14). Flow responses of trees have been most frequently studied in the Verde basin (seven of fifteen). Only one study quantified flow needs and flow responses of herbaceous species. Studies in the Verde River basin quantified relationships between streamflow, water temperature, groundwater availability, and flood size or frequency and the ecosystem.

In the **Bill Williams River** basin, 14 studies of environmental water needs were found with a relatively even number in each study type (Figure 10; Table 1). Flow needs and flow responses are quantified for the Bill Williams River basin (Table 5). Twice as many studies of the Bill Williams basin focused on riparian water needs than on aquatic water needs, and three studies surveyed both riparian and aquatic water needs (Figure 9). Of all river basins in Arizona, holistic methods were used the most extensively in the Bill Williams River basin (Figure 11). Papers using holistic methods in the Bill Williams River basin include BWRC Technical Committee (1994) and Hautzinger et al. (2006).

The water needs of every taxonomic group we considered have been studied quantitatively in the Bill Williams River basin (Figure 15). Trees, shrubs, and birds were the most studied, both in terms of flow needs and flow responses. In the Bill Williams River basin, flow needs and flow responses have been studied with similar frequency. Five studies focus on surface flow magnitude, and three on timing of surface flows, as the most important hydrological element affecting ecological responses. Only four studies of the 14 in the Bill Williams basin consider groundwater connections with biota. This is likely because the water management situation in this basin primarily involves the potential for dam releases that benefit the ecosystem, and less concern exists about the potential for water table drawdown, or lowering of groundwater levels.

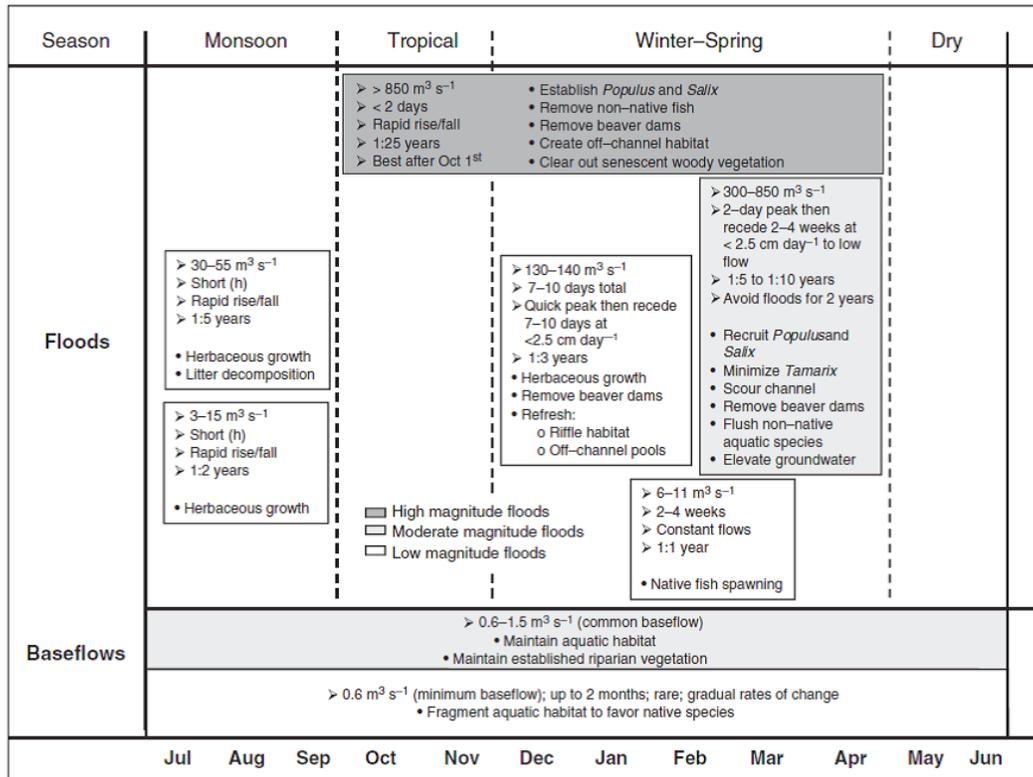
Hautzinger et al. (2006) provides unified flood and baseflow requirements for the Bill Williams River (Figure 16).

Figure 15. Number of Studies Quantifying Flow Needs and Responses in the Bill Williams River Basin



This is the only study in the inventory that provides quantitative flow prescriptions for all five components of flow. The flow requirements represent a “unified,” or merged, set of requirements developed independently by groups considering the needs of aquatic species, riparian bird species, and riparian non-bird species on the Bill Williams River. These flow requirements are presented in terms of the purpose, timing, size, frequency, and duration of flows needed for the Bill Williams River ecosystem.

Figure 16. Holistic Flow Prescription for Bill Williams River

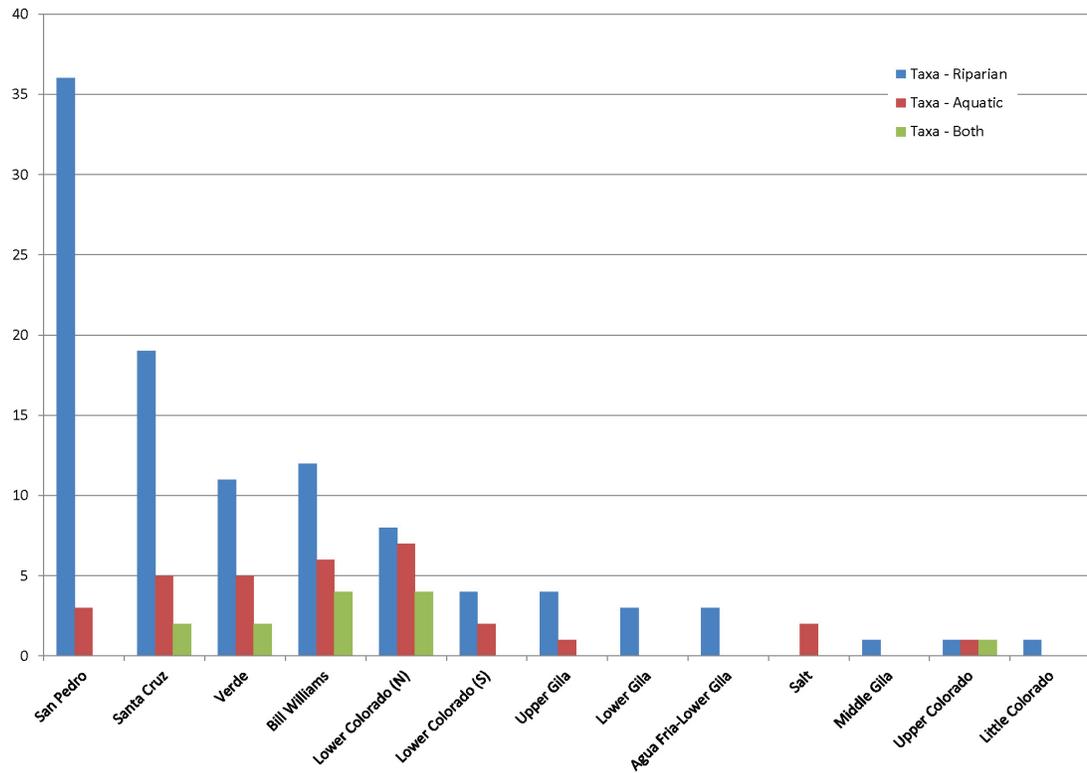


According to experts, small floods, which range from 3 m³/s to 140 m³/s (106 ft³/s to 3672 ft³/s), should occur annually to every five years. Small floods of this size and frequency are believed to improve herbaceous growth, litter decomposition, fish spawning, and beaver dam removal and other forms of general cleansing. Moderate floods, which range from 300 m³/s to 850 m³/s (10594 ft³/s to 30017 ft³/s), are needed every five to ten years to stimulate mixed recruitment of cottonwood and willow. Large floods, which are greater than 850 m³/s (30017 ft³/s), occurring approximately every 25 years should lead to nonnative fish blowouts (high flows that remove fish) and affect the distribution of woody vegetation.

After the top four basins studied, the remaining basins have eight or fewer quantitative studies of water needs--all have more studies of flow responses than flow needs and rarely have multiple studies on each taxonomic group (Table 6). The less studied basins tended to have fewer review and synthesis papers and more single studies. The Lower Colorado (Lees Ferry) River basin, which covers Grand Canyon National Park, proportionately has more single study papers of any other basin.

All basins except the Salt River basin (which had zero) had at least as many studies of riparian water needs as they did of aquatic water needs (Figure 17). The Lower Colorado (Lees Ferry) River section had the most even representation of studies across riparian and aquatic taxa. Outside of the top four river basins, birds were only studied in the Upper and Middle Gila River basins; insects were studied only in the Upper Colorado and Upper Gila; and fish were only studied in the Lower Colorado, Salt, and Upper Colorado basins (Figure 9).

Figure 17. Taxonomic Group Studied by Basin



ADDITIONAL COMMENTS

By conducting this assessment it has become clear what areas of environmental flow needs have been well documented and what areas still need supplemental research in order to achieve a sufficient understanding of environmental water needs. While inventory studies describe some components of environmental water needs quantitatively, including plant water use rates, groundwater depth limits to species survival, and river flow speeds and temperatures needed by native fish, ecosystem-level flow requirements remain poorly known. The Bill Williams River basin is the only basin with a range of seasonal flow volumes prescribed for a whole river. Other river basins, like the Santa Cruz, have at best small scale studies that prescribe flows for a single stream reach.

In some cases, flow recommendations may be transferable across systems, while in others the recommendations are clearly tied to the system that was studied. Findings about the depth to groundwater required to sustain riparian trees (Table 8) are likely to be similar across basins if species remain the same. Mature cottonwood and willow trees seem to prefer groundwater depths between one and three meters, but will withstand water table depths up to six meters. Evapotranspiration rates for riparian trees range between 375 and 2000 mm/year (Table 7). Even the frequency of flood events needed for riparian vegetation recruitment appears somewhat similar across systems: 5-10 years according to Hautzinger et al. (2006) and 10-15 years according to Briggs (2008). Native fish in two basins are known to prefer flow velocities between 0.1 and 0.4 m/s; perhaps they exhibit similar preferences everywhere they occur.

Unlike species-specific studies, estimates of riparian vegetation water use along the San Pedro River are based on estimates of vegetation extent specific to that river. Similarly, studies such as Hautzinger et al. (2006) and NPS (2008) offering flow volume requirements for a specific river reach provide a model for what may need to be done in other basins, but their findings cannot be directly applied elsewhere. National Park Service (2008) indicates that in Rincon Creek, flows of 0.6 m³/s (19.7 ft³/s) would maintain pool habitats needed for a range of native species. This finding is only applicable in the channel morphology of the subject stream, as a flow of 0.6 m³/s would not

necessarily create pool habitats in other stream settings. Despite its limitations in transferability, basin- or reach-level information has an important use where it represents spatial (mapped) conditions on the ground. These studies may be useful for informing small, local water projects to preserve or restore aquatic and riparian habitat.

To some extent, the picture of Arizona's environmental water needs is not clear at a statewide scale. Arizona's aquatic systems remain poorly understood, given their less frequent treatment in e-flows studies. Researchers differ in the ways they measure elements of flow, generating findings that cannot be compared. Even when the measurement is the same, estimates of plant water use rates, groundwater depth limits, and river flow speeds needed by fish frequently differ. In basins where only one study has been done on each taxonomic group, findings about flow needs may have lower confidence. In addition, various aspects of flow (e.g. minimum flow) are studied more frequently in some systems than others (e.g. seasonality of flows). This has the potential to skew our awareness of stressors towards those that are often studied rather than those that are unknown, and yet may still be harmful.

Nonetheless, areas of agreement have emerged across the geographical range of studies. The importance of water to riparian areas has been aptly demonstrated as involving more than groundwater availability. Flood flows are needed to stimulate riparian recruitment and must come at the right time (generally early summer). Lower magnitude baseflows are critical to sustain groundwater levels and associated riparian fauna.

Only one basin (Verde) had multiple studies identifying the importance of water temperature to river and riparian health, but temperature is likely important for all streams and rivers. This issue points to one of the limitations of the current state of the knowledge: just because studies have not been done on a certain aspect of e-flows does not mean that aspect of flow is not important. On the contrary, it appears that every aspect of flow (magnitude, frequency, duration, timing, and rate of change) can have an impact on Arizona's aquatic and riparian ecosystems if it is altered beyond the range of tolerance of native species. With this in mind, water managers in river basins with limited resources for identifying critical flow thresholds for ecosystem health may need to look to other basins for initial guidance.

Those working at a larger (e.g. basin-wide) scale will want to explore the studies completed in their basin and look for key quantitative (and transferable) findings about ecological flow needs and flow responses. Understanding pieces like total plant community groundwater use and determining quantitative holistic flow prescriptions for basins other than where they have already been developed will take time, but the information in this Assessment Report and companion Methodology Guidebook should aid researchers in identifying and filling these information gaps.

INFORMATION GAPS - WHAT DON'T WE KNOW?

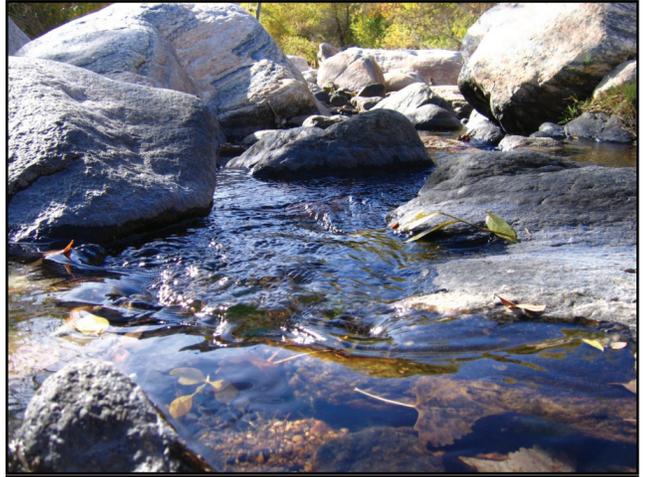
Based on the extent of e-flows studies done around the state (Figure 10), many river basins in Arizona lack a strong literature base defining environmental water needs. The Lower Gila, Salt, Middle Gila, and Upper Colorado Rivers are associated with fewer than five studies each. No data were found from the Little Colorado River basin, though there is evidence that studies have been done there by the Zuni tribe (Briggs 2010).

How much water is needed to support all of Arizona's aquatic and riparian species? Although many streams in Arizona have been dewatered, the paucity of aquatic water needs studies around the state indicates a true information gap. Additionally, basins where riparian water needs have not been studied (Salt and Little Colorado Rivers) indicate information gaps, if only to determine whether findings from other basins hold true. Specifically, the limited knowledge base about animal and insect (as opposed to plant) water needs should be addressed.

The number of holistic studies, or those where ecosystem-level flow needs or flow responses are synthesized, is also low. While studies of environmental water needs in Arizona generally do consider more than one species, they tend not to consider flows needed for both aquatic and riparian species together. Additionally, given the proven influence of groundwater on aquatic and riparian ecosystems, most river basins (with the exception of the San

Pedro and the Santa Cruz) could benefit from additional studies of groundwater influences.

Finally, an obvious information gap is that the future of the water needed to maintain habitats is not clear, especially habitats shown to be of direct value to humans. Studies valuing riparian and aquatic ecosystem elements have rarely defined water allocation in a way that links water needs directly with valued ecosystem elements, making allocation decisions especially difficult.



Sabino Canyon, Tucson, AZ. Photo Credit: Jane Cripps

III. NEXT STEPS

RECOMMENDED ANALYSES

The database developed for the Arizona Environmental Water Needs Assessment is a substantial source of information regarding the universe of existing studies. However, while we have identified a vast array of research on this topic, the statewide picture of environmental water needs has critical data gaps. To truly make the information useful for water managers and scientists, more work is needed to identify barriers to increasing knowledge about Arizona e-flows and where (and how) existing information can be applied to new contexts.

Using detail about each study available in the inventory, critical information gaps and key areas of agreement can be clarified further. A **focused analysis of study extent by river basin** may illuminate whether even those frequently studied basins (like the San Pedro) have reaches that are underrepresented. While we have mapped the extent of all studies included in our analysis, a review of additional and anticipated studies (Appendix B) will expand the knowledge of where environmental water needs have been defined across the state. Next, by linking study findings with their location, we can begin to visualize where the information is available across Arizona in greater detail.

In basins and reaches where environmental water needs have been fully outlined, these **needs can be compared to current conditions** to determine if ecological elements are being maintained or are under stress. Areas in need of protection or restoration will emerge from this analysis. This information can then be communicated to policy making processes and the public to engage in addressing these environmental water needs.

Now that this report has outlined the scope of Arizona's environmental water needs studies and highlighted some key findings, a future inquiry might **further compare detailed data findings** by taxonomic group studied and method used to better represent what is known. Flow responses in particular could be summarized to catalogue relationships between specific flow components, taxa, and categories of flow response. This might follow the approaches used by Turner et al. (2008) and Poff et al. (2010) where they described the general direction or trend of flow responses observed for various taxonomic groups.

Analysis of levels of agreement can begin by considering frequently studied reaches with more than one study on a given topic. This analysis would identify differences and similarities across research papers in order to then delineate ranges of flow needs and flow responses for specific species or biotic communities with higher confidence. One barrier to this effort is the lack of a set of standard measures being used to define environmental water needs. To coordinate future flow studies on a species, river basin, or even across the state, researchers should agree on a common set of measurements appropriate for their areas of focus.

Using Hautzinger et al. (2006) as a model, another key next step would be an analysis of **how far each basin remains from quantifying the whole river basin's environmental water needs**. Then, existing information can be used to fill in these gaps. The setting of each study predictably influences its findings and where these findings can be applied. A good quality spatial dataset representing environmental variables of streams such as climate, geomorphology, and gradient (elevation change) should be created. This map would provide the foundation for a **cross-basin meta-analysis of flow needs and responses** to determine how findings about e-flows are related to the setting being studied.

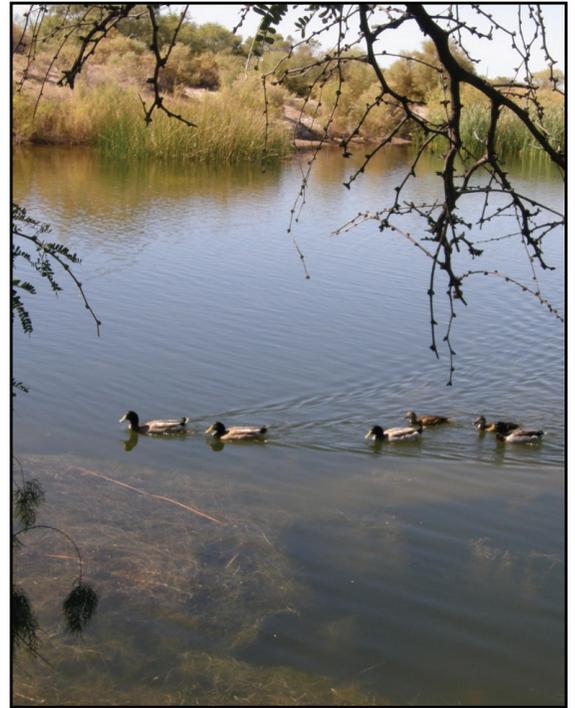
A **scientific rule set for applying e-flows knowledge** across Arizona can ensure that managers use the right studies for reference. Kennard et al. (2010) have suggested a framework for classifying rivers in order to facilitate sharing of e-flows data across a region. The classification is based on flow regime types and considers seasonal flow patterns, degree of flow permanence, and flood size, variation and frequency. Geographic, climatic, and topographic factors can help in classifying Arizona's streams. Those seeking to undertake management decisions or scientific investigations will want to refer to studies done in similar settings, particularly if little information is available for their river basin.

In addition to the physical setting, **the management, or flow regulation, setting** may also guide the use of available information. For example, those managing regulated rivers (e.g. with dams or ditches) specifically for e-flows will want to know duration of flood inundation and rates of regression needed to maintain a natural flow regime. In over allocated systems without dams, more interest may emerge for maintaining the necessary minimum flows.

A Methodology Guidebook has been developed to help with the selection and implementation of environmental water need methodologies. However, in addition to the information presented there, more detail about the cost of these studies (perhaps the average amount spent for each method employed) would benefit potential users. Focusing on the methods used for each study, individual studies could be categorized using the methods evaluation information presented in the companion Methodology Guidebook. Mapping the linked attributes would show spatially **what decision types are supported across river basins/streams.**

Studies that describe the movement of water through a particular river system (such as Kepner et al. 2004; Ward 2008; Haney et al. 2009) were not included in this analysis, as they do not describe environmental water needs in any detail. Hydrological studies, such as groundwater models or water budgets, could be used in conjunction with our inventory to determine potential threats to environmental water needs or potential sources of water for the environment (e.g. Leake et al. 2008 for the San Pedro River). The studies in our inventory provide **additional information within their analyses about information gaps and research needs** as well as recommendations for water management.

Finally, having all the information needed to understand environmental water needs is just one step in addressing these water needs. It is unrealistic to think that this assessment on its own provides all the tools water managers need to balance often competing demands. A key next step will be **building decision making tools** using the information from our inventory. Examples of best practices in applying e-flow knowledge to water management and decision making may be found in other systems around the nation and the globe. These examples could guide the development and use of this information in Arizona.



Lower Salt River, Mesa, AZ. Photo Credit: Brittany Choate.

HOW TO START?

Based on input from experts and stakeholders engaged throughout our process, it appears that two major tasks should be completed:

(1) *Studies of the basic water needs and flow responses of riparian and aquatic species* should be initiated in river basins that have a limited e-flow information base and impending water conflicts (Figure 10). Additionally, in basins where a given species or group of species is specifically known to be threatened, more studies of that group's water needs should be planned. The most understudied taxonomic groups (such as mammals, amphibians, and reptiles) require immediate attention, given that they are known to frequent riparian areas. Any organism in our riparian and aquatic system that we are committed to preserving will need quantitative study of its flow needs in order to ensure its survival. Where possible, use of indicator species or flow-response guilds (or groups) to represent the flow needs of larger groups of organisms is recommended. Development of a standard set of measurements to ensure consistency in definitions of environmental water needs is also needed. Finally, if a stream classification can be developed to guide application of study findings across river basins, this may supplant the need for more basin-specific studies.

(2) Water demands in all sectors are increasing, so protection of rivers and riparian ecosystems is time-sensitive. *To prioritize the protection of water for the environment, factors putting these needs at immediate risk should be identified.* A comparison of e-flow needs with current conditions will highlight areas needing protection or restoration. One approach suggested by our advisory committee for preventing further degradation would be to survey water managers and major water users about water decisions they are facing and identify potential conflicts between these decisions and environmental water needs. Another approach would be to use existing groundwater models and water budgets to identify water movement patterns that, if disrupted, would immediately threaten existing environmental water uses.

Efforts are underway to describe the needs of all water sectors statewide. Our assessment provides critical information that can be used in those discussions and others like it to ensure that the water needs of the environment are appropriately considered. In addition to demonstrating the importance of multiple components of flow (flood timing, groundwater availability, water quality), our assessment provides initial estimates of environmental water demands in particular basins. While a single quantity for statewide environmental demand does not automatically emerge from this survey, many pieces of major environmental water uses have been quantified. With a few basic assumptions, appropriate application of these numbers across river basins will provide an initial approximation of overall environmental water demand. This exercise seems comparable to those estimates made of crop water usage or exempt groundwater well pumping: it is not a perfect science, but it can help start the discussion.

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APPENDICES

- A. Glossary
- B. List of Studies by River Basin
- C. Additional and Anticipated Studies

APPENDIX A. GLOSSARY

- Amphibians - A cold-blooded, smooth-skinned vertebrate of the class Amphibia, such as a frog or salamander that characteristically hatches as an aquatic larva with gills
- Aquatic - Living or growing in, on, or near the water
- Baseflow - The portion of stream flow entering the channel from a groundwater source
- Biodiversity - The variability among living organisms from all sources
- Biological - Of or relating to life or living things
- Biomass - The amount (mass) of living biological organisms in a given area and time, this can be expressed as an average or total amount per unit area
- Biota - The plant and animal life of a region
- Bottomland - Low lying, often fertile land near a water system
- Community - A group of interacting organisms that share a common environment
- Discharge - Volume rate of water flow
- Ecology - The science of observing relationships between organisms and their environment
- Ecosystem - An interacting community of living organisms and nonliving physical components of an environment
- Environmental flows - The amount of water needed in a watercourse to sustain a healthy ecosystem
- Evapotranspiration - The sum of evaporation and plant transpiration from the Earth's land surface to atmosphere
- Facultative phreatophyte - Plant that uses a mix of groundwater and soil water derived from rainfall or flood pulses as their water sources
- Fauna - All of the animal life of any particular region
- Floodplain - Flat or nearly flat land adjacent to a waterway that has been built up by historical flood events through mud and rock deposits and is subject to flooding
- Flow rate - The speed at which water in a river is travelling down the river (often reported in feet/second)
- Flow regime - Encompasses the following characteristics of stream flow and their interactions: magnitude, timing, frequency, duration, and rate of change
- Fluvial - Processes associated with rivers and streams and the deposits and landforms created by them
- Gage - Records flow in a stream or river
- Geographic - Of or relating to the science of studying the earth and its physical characteristics
- Geomorphic - Relating to earth forms
- Geomorphology - The study of present-day landforms and their relationships to underlying structures (this includes their classification, nature, origin, development, etc.)

Gradient - A series of progressively increasing or decreasing differences in the environment

Groundwater - Water beneath the earth's surface, often between saturated soil and rock, that supplies wells, springs, and some streams

Herbaceous - A plant that does not have a permanent woody stem (i.e. a flowering plant or an herb)

Hydraulic - Of or relating to the properties of water in motion, or flow

Hydroclimatology - The study of the temperature, precipitation, and potential evapotranspiration levels within a watershed

Hydrogeologic - Part of hydrology that deals with the distribution and movement of groundwater in the soil and rocks of the Earth's crust

Hydrogeomorphic - Relating to hydrologic, biogeochemical, and habitat functions

Hydrograph - Graph showing changes in the discharge of a river over a period of time

Hydrologic - The properties, distribution, and effects of water on the earth's surface, in the soil and underlying rocks, and in the atmosphere

Hyporheic zone - Region under and beside a stream channel or floodplain that contains water that is freely exchanged with the surface flow in the stream; i.e. the area where surface water and groundwater interacts

Instream flows - The water in a stream

Interannual - Over several years; regarding water year types

Intraannual - Within a year; seasonal

Irrigation - Supplying dry land with water by means of ditches and streams

Lentic - Of a lake, pond, or swamp

Litter - Dead plant material (i.e. leavers, twigs, or bark) that has fallen to the ground; often provides habitat and is a source of nutrients for the environment

Lotic - Of a river, stream, or spring

Macroinvertebrate - An invertebrate that is large enough to be seen without the use of a microscope

Non-fluvial - Processes not associated with rivers and streams, such as landslides, debris flows, etc.

Non-phreatophyte - Plant that relies strictly on rain or flood water

Obligate phreatophyte - Plant that uses groundwater as their primary water sources

Phreatophyte - A deep-rooted plant that obtains a significant portion of the water that it needs from the phreatic zone (zone of saturation)

Pools - Slow-moving, deeper water over finer-grained substrates
Population – A group of organisms that both belong to the same species and live in the same geographical area

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- Qualitative - A description or distinction based on a quality or characteristic rather than quantity or measured value
- Quantitative - A description of distinction based on quantities or measured values rather than a characteristic
- Regulated river - A river or creek whose flow is determined primarily by a major dam
- Remote sensing - The science of identifying, observing, and measuring an object without coming into direct contact with it; often using satellites
- Reptiles - Animals characterized by breathing air, laying shelled eggs, and having skin covered in scales
- Riffles - Fast-moving, higher-gradient, shallower water over coarse sand/gravel/cobble substrate
- Riparian - Of or relating to or located on the banks of a river or stream
- River reach - A river or stream segment of a specific length
- River segment - A portion of a river that lies between two established points
- River stage - The height of the surface of a river or other fluctuating body of water above a set point
- Runs - Moderate velocity, moderate depth water over coarse- to medium-sand substrate
- Sedimentation - The tendency for solid particles in a liquid to settle out of the fluid and come to rest against a barrier
- Spatial - Pertaining to space (i.e. global, state, regional, etc.)
- Species - A group of organisms that share similar traits and are capable of interbreeding and producing fertile offspring; the basic category of biological classification
- Stable isotopes - Nuclei that do not appear to decay to other isotopes on geologic timescales, but may themselves be produced by the decay of radioactive isotopes, used to identify source locations of water
- Stratigraphy - A branch of geology that studies rock layers and layering
- Stream flow - The volume of water moving down the river over a given time period (often reported in cubic feet/second)
- Stream margin - The wet area seeping water into a stream characterized by shallow depths and slow moving water
- Subwatershed or Subbasin - Extent of land where water from rain and melting snow or ice drains downhill into a body of water, such as a river or lake; smaller unit of a watershed
- Surface water - Surface water is water collecting on the ground or in a stream, river, lake, wetland, or ocean
- Taxa - Plural form of taxon; a population or group of populations that are phylogenetically related and have common characteristics that differentiate them from other such groups (i.e. the kingdom, phylum, class, order, family, genus, or species)
- Taxonomic group - A group of populations that are phylogenetically related and have common characteristics that differentiate them from other such groups (i.e. the kingdom, phylum, class, order, family, genus, or species)
- Temporal - Pertaining to time
- Terrestrial - Of or relating to the earth; inhabiting the land as opposed to the sea or air

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Thalweg - Signifies the deepest continuous line along a valley or watercourse.

Unregulated - An unregulated river flows according to gravity from its source to the mouth and is not interrupted by dams or hydroelectric power

Water table - The upper limit of the saturated zone within an aquifer

Watershed or River basin or Stream network - The area of land where all of the water that is under it or drains off of it goes into the same place

APPENDIX B. LIST OF STUDIES BY RIVER BASIN

1) **Agua Fria**

a) Quantitative

i) Riparian

- (1) Horton, J.L.; Kolb, T.E.; Hart, S.C. 2001. "Physiological response to groundwater depth varies among species and with river flow regulation"
- (2) Horton, J.L.; Kolb, T.E.; Hart, S.C. 2001. "Responses of riparian trees to inter annual variation in ground water depth in a semi-arid river basin"

ii) Both Riparian and Aquatic

- (1) Springer, et al. 1999. "Coupling groundwater and riparian vegetation models to assess effects of reservoir releases"

2) **Bill Williams**

a) Quantitative

i) Riparian

- (1) Merritt, D.M.; Poff, N.L. 2010. "Shifting dominance of riparian Populus and Tamarix along gradients of flow alteration in western North American rivers"
- (2) Shafroth; Beauchamp. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Streamflow-Biota Relations: Riparian Vegetation (Chapter 3)"
- (3) Horton, J.L.; Kolb, T.E.; Hart, S.C. 2001. "Physiological response to groundwater depth varies among species and with river flow regulation"
- (4) Shafroth, P.B.; Auble, G.T.; Stromberg, J.C.; Patten, D.T. 1998. "Establishment of woody riparian vegetation in relation to annual patterns of streamflow, Bill Williams River, Arizona."
- (5) Busch; Smith. 1995. "Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern U.S."

ii) Both Riparian and Aquatic

- (1) Shafroth et al. 2010. "Ecosystem effects of environmental flows: modeling and experimental floods in a dryland river"
- (2) Hautzinger; Warner; Hickey; Beauchamp. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Summary of Unified Ecosystem Flow Requirements for the Bill Williams River Corridor (Chapter 8)"
- (3) van Riper; Paradzick. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Stream flow-Biota Relations: Birds (Chapter 4)"

(4) BWRC Technical Committee. 1994. "Bill Williams River Water Management Plan"

b) Qualitative

i) Riparian

(1) Andersen. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Streamflow-Biota Relations: Mammals, Reptiles, Amphibians, and Flood plain Invertebrates (Chapter 6)"

ii) Aquatic

(1) Lytle. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Streamflow-Biota Relations: Fish and Aquatic Macroinvertebrates (Chapter 5)"

iii) Both Riparian and Aquatic

(1) Hautzinger, et al. 2008. "How much water do stream-dependent species need?"

(2) Andersen. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Ecosystem Functioning (Chapter 7)"

(3) Shafroth; Beauchamp. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Background and Introduction (Chapter 1)"

3) Lower Colorado

a) Quantitative

i) Riparian

(1) Merritt, D.M.; Poff, N.L. 2010. "Shifting dominance of riparian Populus and Tamarix along gradients of flow alteration in western North American rivers"

(2) Ralston, B.E. 2010. "Riparian vegetation response to the March 2008 short-duration high-flow experiment- Implications of timing and frequency of flood disturbance on nonnative plant established along the Colorado River below Glen Canyon Dam."

(3) Kearsley, M.J.C.; Ayers, T.J. 2009. "Riparian vegetation responses: snatching defeat from the jaws of victory and vice versa."

(4) Busch; Smith. 1995. "Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern U.S."

ii) Aquatic

(1) Korman, J.; Kaplinski, M.; Melis, T.S. 2010. "Effects of high-flow experiments from Glen Canyon Dam on abundance, growth, and survival rates of early life stages of rainbow trout in the Lees Ferry Reach of the Colorado River"

(2) Rosi-Marshall, E.J.; Kennedy, T.A.; Kincaid, D.W.; Cross, W.F.; Kelly, H.A.W.; Behn, K.A.; White, T.; Hall Jr., R.O.; Baxter, C.V. 2010. "Short-term effects of the 2008 high-flow experiment on macroinvertebrates in Colorado River below Glen Canyon Dam, Arizona"

(3) Marcus. 2009. "Glen Canyon Dam Releases - Economic Considerations"

(4) U.S. Fish and Wildlife Service. 2008. "Final Biological Opinion for the Operation of the Glen Canyon Dam"

(5) Minckley, W.L.; Meffe, G.K. 1987. "Differential Selection by Flooding in Stream-fish communities of the arid American Southwest"

iii) Both Riparian and Aquatic

(1) Hautzinger, et al. 2008 "How much water do stream-dependent species need?"

(2) Tallent-Halsell, N.G.; Walker, L.R. 2002. "Responses of *Salix gooddingii* and *Tamarix ramosissima* to flooding"

(3) Valdez, R.A.; Shannon, J.P.; Blinn, D.W. 1999. "Biological implications of the 1996 Controlled Flood"

(4) Schmidt, J.C.; Webb, R.H.; Valdez, R.A.; Marzolf, G.R. 1998. "Science and values in river restoration in the Grand Canyon"

b) Qualitative

i) Aquatic

(1) GCWC. 2001. "An Inventory of Arizona Strip Seeps, Springs, and Ponds"

ii) Both Riparian and Aquatic

(1) Bureau of Reclamation. 2008. "Final environmental assessment experimental releases from Glen Canyon Dam, Arizona 2008-2012"

4) Lower/Middle Gila

a) Quantitative

i) Riparian

(1) Koronkiewicz, T.J.; Graber, A.E.; McLeod, M.A. 2010. "Variation in streamflow influences abundance and productivity of an endangered songbird, the southwestern willow flycatcher"

(2) Merritt, D.M.; Poff, N.L. 2010. "Shifting dominance of riparian *Populus* and *Tamarix* q along gradients of flow alteration in western North American rivers"

(3) Horton, J.L.; Kolb, T.E.; Hart, S.C. 2001. "Physiological response to groundwater depth varies among species and with river flow regulation"

(4) Horton, J.L.; Kolb, T.E.; Hart, S.C. 2001. "Responses of riparian trees to interannual variation in ground water depth in a semi-arid river basin."

ii) Both Riparian and Aquatic

(1) Springer, et al. 1999. "Coupling groundwater and riparian vegetation models to assess effects of reservoir releases"

5) Salt

a) Quantitative

i) Aquatic

- (1) USGS; Waddle. 2009. "Environmental Flow Studies of the Fort Collins Science Center - Cherry Creek, Arizona"
- (2) Minckley, W.L.; Meffe, G.K. 1987. "Differential Selection by Flooding in Stream-fish communities of the arid American Southwest"

6) San Pedro

a) Quantitative

i) Riparian

- (1) Brand, L.A.; Stromberg, J.C.; Goodrich, D.C.; Dixon, M.D.; Lansey, K.; Kang, D.; Brookshire, D.S.; Cerasale, D.J. 2010. "Projecting avian response to linked changes in ground water and riparian floodplain vegetation along a dryland river: a scenario analysis"
- (2) Merritt, D.M.; Poff, N.L. 2010. "Shifting dominance of riparian Populus and Tamarix along gradients of flow alteration in western North American rivers"
- (3) Hannon, L.E.; Ries, L.; Williams, K.S. 2009. "Ecology and Conservation of the San Pedro River - Terrestrial arthropod communities along the San Pedro: Three Case Studies (Chapter 7)"
- (4) Kirkpatrick, C.; Conway, C.J.; LaRoche, D. 2009. "Quantifying impacts of groundwater with drawal on avian abundance, species richness, and reproductive success in Sonoran Desert Parks (DRAFT)"
- (5) Kirkpatrick, C.; Conway, C.J.; LaRoche, D. 2009. "Surface water depletion and riparian birds"
- (6) Stromberg; Dixon; Scott; Maddock; Baird; Tellman. 2009. "Ecology and Conservation of the San Pedro River - Status of the Upper San Pedro River (United States) Riparian Ecosystem (Chapter 20)"
- (7) Stromberg, J.C.; Lite, S.J.; Dixon, M.D. 2009. "Effects of stream flow patterns on riparian vegetation of a semiarid river: Implications for a changing climate"
- (8) Stromberg; Lite; Dixon; Tiller. 2009. "Ecology and Conservation of the San Pedro River - Riparian vegetation: Pattern and Process (Chapter 1)"
- (9) Williams, D.G.; Scott, R.L. 2009. "Ecology and Conservation of the San Pedro River - Vegetation-hydrology interactions: Dynamics of riparian plant water use (Chapter 2)"
- (10) Sabo, J.L.; McCluney, K.E.; Marusenko, Y.; Keller, A.; Soykan, C.U. 2008. "Greenfall links groundwater to aboveground food webs in desert river floodplains."
- (11) Scott, R.L.; Cable, W.L.; Huxman, T.E.; Nagler, P.L.; Hernandez, M.; Goodrich, D.C. 2008. "Multiyear riparian evapotranspiration and groundwater use for a semiarid watershed."

- (12) Stromberg. 2008. "Verde River Ecological Flows Study - Background: Stream Flow Regimes and Riparian Vegetation of the Verde River (Chapter 4)"
- (13) Kirkpatrick, C.; Conway, C.J.; LaRoche, D. 2007. "Quantifying impacts of groundwater with drawal on avian communities in desert riparian woodlands of the southwestern U.S."
- (14) Gazal, R.M.; Scott, R.L.; Goodrich, D.C.; Williams, D.G. 2006. "Controls on transpiration in a semiarid riparian cottonwood forest."
- (15) Shafroth; Beauchamp. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Streamflow-Biota Relations: Riparian Vegetation (Chapter 3)"
- (16) ADWR. 2005. "Groundwater use estimates for riparian inventory of the Benson sub-area - Appendix E"
- (17) Bagstad, K.J.; Stromberg, J.C.; Lite, S.J. 2005. "Response of herbaceous riparian plants to rain and flooding on the San Pedro River, Arizona, USA"
- (18) Lite, S.J.; Bagstad, K.J.; Stromberg, J.C. 2005. "Riparian plant species richness along lateral and longitudinal gradients of water stress and flood disturbance, San Pedro River, Arizona, USA."
- (19) Lite; Stromberg. 2005. "Surface water and ground-water thresholds for maintaining Populus-Salix forests, San Pedro River, Arizona"
- (20) Stromberg et al. 2005. "Effects of stream flow intermittency on riparian vegetation of a semiarid region river (San Pedro River, Arizona)"
- (21) Scott, R.L.; Goodrich, D.C.; Levick, L.R. 2003. "A GIS-based management tool to quantify riparian vegetation groundwater use"
- (22) Stromberg, J.; Lite, S.; Beauchamp, V. 2003. "Managing stream flow regimes for riparian ecosystem restoration"
- (23) Stromberg, J.C. 2001. "Biotic integrity of Platanus wrightii riparian forests in Arizona: first approximation"
- (24) Goodrich, D.C.; Scott, R.; Qi, J.; Goff, B.; Unkrich, C.L.; Moran, M.S.; Williams, D.; Schaeffer, S.; Snyder, K.; MacNish, R.; Maddock, T.; Pool, D.; Chehbouni, A.; Cooper, D.I.; Eichinger, W.E.; Shuttleworth, W.J.; Kerr, Y.; Marsett, R.; Ni, W. 2000. "Seasonal estimates of evapo transpiration using remote and in site measurements."
- (25) Scott, R.L.; Shuttleworth, W.J.; Goodrich, D.C.; Maddock III, T. 2000. "The water use of two dominant vegetation communities in a semiarid riparian ecosystem"
- (26) Stromberg, J.C.; Tiller, R.; Richter, B. 1996. "Effects of groundwater decline on riparian vegetation of semiarid regions: The San Pedro, Arizona"

ii) Aquatic

- (1) Minckley, W.L.; Meffe, G.K. 1987. "Differential Selection by Flooding in Stream-fish communities of the arid American Southwest"

iii) Both Riparian and Aquatic

- (1) Katz, G.L.; Stromberg, J.C.; Denslow, M.C. 2009. "Streamside herbaceous vegetation response to hydrologic restoration on the San Pedro River, Arizona"
- (2) Pima County. 2009. "City of Tucson and Pima County Riparian Protection Technical Paper"
- (3) Pima County. 2009. "City of Tucson and Pima County Water for the Environment Technical Paper"
- (4) Leake, S.A.; Pool, D.R.; Leenhouts, J.M. 2008. "Simulated effects of groundwater withdrawals and artificial recharge on discharge to streams, springs, and riparian vegetation in the Sierra Vista subwatershed of the Upper San Pedro Basin, Southeastern Arizona."
- (5) Leenhouts et al. 2006. "Hydrologic Requirements of and Consumptive Ground-water Use by Riparian Vegetation along the San Pedro River, Arizona"
- (6) Fonseca, J. 2004. "Aquifer monitoring for groundwater-dependent ecosystems, Pima County, Arizona"
- (7) Orr, P.; B. Colby. 2002. "Expenditures by nature-oriented visitors and their economic implications in the Upper San Pedro River Valley"
- (8) Pima County. 2000. "Preliminary Riparian Protection, Management, and Restoration Element"

b) Qualitative

i) Riparian

- (1) Rosen, P.C. 2009. "Ecology and Conservation of the San Pedro River - Reptiles and Amphibians (Chapter 9)"
- (2) Soykan, C.U.; Brand, L.A.; Sabo, J.L. 2009. "Ecology and Conservation of the San Pedro River - Causes and consequences of mammal species richness (Chapter 6)"

ii) Aquatic

- (1) Stefferud, J.A.; Marsh, P.C.; Stefferud, S.E.; Clarkson, R.W. 2009. "Ecology and Conservation of the San Pedro River - Fishes: Historical changes and an imperiled fauna (Chapter 10)"

iii) Both Riparian and Aquatic

- (1) Brand, L.A.; Cerasale, D.J.; Rich, T.D. 2009. "Ecology and Conservation of the San Pedro River - Breeding and Migratory Birds: Patterns and Processes (Chapter 8)"
- (2) Haney, J. 2005. "The Lower San Pedro River - Hydrology and flow restoration for biodiversity conservation"

7) Santa Cruz

a) Quantitative

i) Riparian

- (1) Kirkpatrick, C.; Conway, C.J.; LaRoche, D. 2009. "Quantifying impacts of groundwater withdrawal on avian abundance, species richness, and reproductive success in Sonoran Desert Parks (DRAFT)"
- (2) Kirkpatrick, C.; Conway, C.J.; LaRoche, D. 2009. "Surface water depletion and riparian birds"
- (3) Scalero, D. 2009. "Final report: Pantano Jungle restoration Cienega Creek Natural Preserve"
- (4) Villarreal, M.L. 2009. "Land use and disturbance interactions in dynamic arid systems: Multiscale remote sensing approaches for monitoring and analyzing riparian vegetation change."
- (5) Bourne, K.L. 2007. "The effect of the Santa Cruz River riparian corridor on single family home prices using the hedonic pricing method"
- (6) Kirkpatrick, C.; Conway, C.J.; LaRoche, D. 2007. "Quantifying impacts of groundwater withdrawal on avian communities in desert riparian woodlands of the southwestern U.S."

ii) Aquatic

- (1) Boyle, T.P.; Fraleigh Jr., H.D. 2003. "Natural and anthropogenic factors affecting the structure of the benthic macroinvertebrate community in an effluent-dominated reach of the Santa Cruz River, AZ"
- (2) Minckley, W.L.; Meffe, G.K. 1987. "Differential Selection by Flooding in Stream-fish communities of the arid American Southwest"

iii) Both Riparian and Aquatic

- (1) Bark, R.H.; Osgood, D.E.; Colby, B.G.; Katz, G.; Stromberg, J. 2009. "Tucson Study of Human Preferences for Riparian Habitat"
- (2) Pima County. 2009. "City of Tucson and Pima County Riparian Protection Technical Paper"
- (3) Pima County. 2009. "City of Tucson and Pima County Water for the Environment Technical Paper"
- (4) Sonoran Institute. 2009. "A Living River: charting the health of the upper santa cruz river, 2008 water year."
- (5) Briggs. 2008. "Water Requirements for Bottomland vegetation of middle Rincon Creek and potential threats to water availability"

- (6) National Park Service. 2008. "Assessment Report Water-Right Application No. 33-96733 For Instream-Flow Maintenance. Middle Reach of Rincon Creek, Pima County, Arizona"
- (7) Briggs, M.K.; Magirl, C.; Hess, S. 2007. "Hydrologic function and channel morphologic analysis of the Santa Cruz River at the North Simpson Site"
- (8) Bark-Hodgins, R.H.; Osgood, D.E.; Colby, B.G. 2006. "Remotely sensed proxies for environmental amenities in hedonic analysis: What does "green" mean? (Chapter 9 in Environmental Valuation)"
- (9) Colby, B.G.; Wishart, S. 2002. "Riparian areas generate property value premium for landowners"
- (10) Fonseca, J. 2004. "Aquifer monitoring for groundwater-dependent ecosystems, Pima County, Arizona"
- (11) Pima County. 2000. "Preliminary Riparian Protection, Management, and Restoration Element"

b) Qualitative

i) Riparian

- (1) Bodner, G.; Simms, K. 2008. "State of the Las Cienegas National Conservation Area: Part 3. Condition and trend of riparian target species, vegetation, and channel geomorphology"

ii) Aquatic

- (1) Bodner, G.; Simms, J.; Gori, D. 2007. "State of the Las Cienegas National Conservation Area: Gila topminnow population status and trends 1989-2005"

iii) Both Riparian and Aquatic

- (1) Norman, L.; Tallent-Halsell, N.; Labiosa, W.; Weber, M.; McCoy, A.; Hirshboeck, K.; Callegary, J.; van Riper III, C.; Gray, F. 2010. "Developing an ecosystem services online decision support tool to assess the impacts of climate change and urban growth in the Santa Cruz watershed; where we live, work, and play."

8) Statewide

a) Quantitative

i) Aquatic

- (1) Carveth, C.J.; Widmer, A.M.; Bonar S.A. 2006. "Comparison of upper thermal tolerances of native and non-native fish species in Arizona."

9) Upper Colorado

a) Quantitative

i) Aquatic

- (1) Melis et al (USGS). 2010. "2008 High-flow experiment at Glen Canyon Dam benefits Colorado River Resources in Grand Canyon National Park"

10) Upper Gila

a) Quantitative

i) Riparian

- (1) Koronkiewicz, T.J.; Graber, A.E.; McLeod, M.A. 2010. "Variation in streamflow influences abundance and productivity of an endangered songbird, the southwestern willow flycatcher"
- (2) Kirkpatrick, C.; Conway, C.J. LaRoche, D. 2009. "Quantifying impacts of groundwater with drawal on avian abundance, species richness, and reproductive success in Sonoran Desert Parks (DRAFT)"
- (3) Kirkpatrick, C.; Conway, C.J. LaRoche, D. 2009. "Surface water depletion and riparian birds"
- (4) Kirkpatrick, C.; Conway, C.J. LaRoche, D. 2007. "Quantifying impacts of groundwater with drawal on avian communities in desert riparian woodlands of the southwestern U.S."

ii) Aquatic

- (1) Minckley, W.L.; Meffe, G.K. 1987. "Differential Selection by Flooding in Stream-fish communities of the arid American Southwest"

11) Verde

a) Quantitative

i) Riparian

- (1) Merritt, D.M.; Poff, N.L. 2010. "Shifting dominance of riparian Populus and Tamarix along gradients of flow alteration in western North American rivers"
- (2) Stromberg. 2008. "Verde River Ecological Flows Study - Background: Stream Flow Regimes and Riparian Vegetation of the Verde River (Chapter 4)"
- (3) Beauchamp, V.B.; Stromberg, J.C. 2007. "Flow regulation of the Verde River, Arizona encourages Tamarix recruitment but has minimal effect on Populus and Salix stand density."
- (4) Stromberg, J.; Lite, S.; Beauchamp, V. 2003. "Managing stream flow regimes for riparian ecosystem restoration"
- (5) Stromberg. 2001. "Influence of stream flow regime and temperature on growth rate of the riparian tree, Platanus wrightii, in Arizona"
- (6) Stromberg, J.C. 2001. "Biotic integrity of Platanus wrightii riparian forests in Arizona: first approximation"
- (7) Stromberg, J.C. 1993. "Instream flow models for mixed deciduous riparian vegetation within a semiarid region"

ii) Aquatic

- (1) U.S. Fish and Wildlife Service. 1989. "Fish and Wildlife Coordination Act Substantiating Report: Central Arizona Project, Verde and East Verde River Water Diversions."

- (2) Minckley, W.L.; Meffe, G.K. 1987. "Differential Selection by Flooding in Stream-fish communities of the arid American Southwest"

iii) Both Riparian and Aquatic

- (1) Haney; Turner. 2008. "Verde River Ecological Flows Study - Synthesis: Verde River Flows and Ecosystem Water Needs (Chapter 7)"
- (2) Stevens et al. 2008. "Verde River Ecological Flows Study - Background: Wildlife and Flow Relationships in the Verde River Watershed (Chapter 5)"
- (3) Turner; Haney. 2008. "Verde River Ecological Flows Study - Workshop Results: Steps Toward Understanding Ecological Response to Hydrologic Variation in the Verde River (Chapter 6)"

b) Qualitative

i) Both Riparian and Aquatic

- (1) West, P.; Smith, D.H.; Auberle, W. 2009. "Valuing the Verde River watershed: an assessment"
- (2) Dwire, K.; Buffington, J.; Merritt, D.; Rieman, B.; Tait, C. 2008. "Upper Verde River: Review of stream-riparian monitoring efforts conducted by the U.S. Forest Service Rocky Mountain Research Station"

APPENDIX C. ADDITIONAL AND ANTICIPATED STUDIES

ADDITIONAL STUDIES (SORTED BY RIVER BASIN)

1) Bill Williams

a) Aquatic

- i) Hautzinger. 2007. "Bill Williams River, Arizona: Restoring Natural Variability in an Arid Lands River"

2) Gila

a) Aquatic

- i) Gookin. 2009. "Annual Virgin Flows in Central Arizona"
- ii) Propst et al. 2008. "Natural Flow Regimes, Nonnative Fishes, and Native Fish Persistence in Arid Land River Systems"
- iii) Stromberg et al. 2007. "Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid south-western United States"

3) Lower Colorado

a) Aquatic

- i) Bureau of Reclamation. 1995-2008. "Lower Colorado River Accounting System Evapotranspiration and Evaporation Calculations"

b) Valuation

- i) Lellouch et al. 2007. "Ecosystem Changes and Water Policy Choices: Four Scenarios for the Lower Colorado River Basin to 2050"

4) Salt

a) Riparian

- i) Fenner. 1985. "Effects of Regulated Water Flows on Regeneration of Fremont Cottonwood"

5) San Pedro

a) Riparian

- i) Brand et al. 2008. "Factors Influencing Species Richness and Community Composition of Breeding Birds in a Desert Riparian Corridor"

b) Aquatic

- i) Snyder; Williams. 2000. "Water sources used by riparian trees varies among stream types on the San Pedro River, Arizona"

c) Water quality

- i) Wahi et al. 2007. "Geochemical quantification of semiarid mountain recharge"

6) Santa Cruz

a) Riparian

- i) Unland et al. 1997. "Evaporation from a Riparian System in a Semi Arid Environment"

b) Aquatic

- i) Freedman, V. 2009. "Evapotranspiration data for Native Plants"
- ii) Goforth; Walker. 2008. "Aquatic invertebrates and their relationship to water availability and stream flow in Middle Rincon Creek, Saguaro National Park East"
- iii) Stitt; Swann; Ratzlaff. 2008. "Aquatic herpetofauna and surface water availability in Rincon Creek, Saguaro National Park, Pima County, Arizona"

c) Holistic

- i) Stromberg, J. C.; Sommerfeld, M. R.; Patten, D. T.; Fry J.; Kramer, C.; Amalfi, F.; Christian, C. 1993. "Release of effluent into the Upper Santa Cruz River, Southern Arizona: Ecological considerations."

7) Statewide

a) Riparian

- i) Anning; Parker. 2009 "Predictive Models of the Hydrological Regime of Unregulated Streams in Arizona"
- ii) Busch et al. 1992. "Water Uptake in Woody Riparian Phreatophytes of the Southwestern United States: A Stable Isotope Study"
- iii) Short, H.L. 1984. Habitat suitability index models: The Arizona guild and layers of habitat models. USFWS OBS-82/10.70. 37 pp.

b) Aquatic

- i) Mortenson and Weisberg. 2010. "Does river regulation increase the dominance of invasive woody species in riparian landscapes?"
- ii) Nagler et al. 2005. "Evapotranspiration on western U.S. rivers estimated using the Enhanced Vegetation Index from MODIS and data from eddy covariance and Bowen ratio flux towers"
- iii) Bryan; Hyatt. 2004. "Roundtail Chub Population Assessment in the Lower Salt and Verde Rivers, Arizona, State Wildlife Grant Final Report"
- iv) Stromberg. 2001. "Restoration of riparian vegetation in the south-western United States: importance of flow regimes and fluvial dynamism"
- v) G.E.P. Smith. 1915. "Discussion of Safe Yield of Groundwater Reservoirs"

ANTICIPATED STUDIES (SORTED BY SUBJECT)

1. Current conditions

a. Statewide

- i. Wissler, C. "Wetlands Mapping." Ongoing.
- ii. Uhlman, K. "Extent of treated wastewater in streams" (AWI report). In Review.

b. Southern Arizona

- i. Turner; Weinstein; Minckley. "Distribution and status of cienegas in southern Arizona and northern Sonora." (in prep) The Nature Conservancy.

c. Little Colorado River

- i. ADEQ 2009. The Water Quality of the Little Colorado River Watershed
- ii. Condon et al., 2010. Ecological Assessment of Streams in the Little Colorado River watershed in Arizona, 2007" (in press)
- iii. Paretto and Robinson. 2007. Ecological Assessment of Streams in the Little Colorado River Watershed, Arizona, Regional Ecological Monitoring and Assessment Program

d. San Pedro River

- i. Turner; Richter. "Wet-Dry mapping: Using Citizen Scientist for Monitoring Streamflow in Arid Regions (11-year analysis of San Pedro Data)." In Review in Environmental Management.

e. Verde River

- i. Ross, Springer, and Schlinger. 2010. Draft Final Report, Phase II Verde Valley Hydraulic Model Project

2. Quantifying environmental water requirements

a. Colorado River

- i. USBR/CADSWES – Instream flow modeling of environmental water needs – report to be (2010?)

b. Salt River

- i. USFS - Riparian vegetation water needs study for Cherry Creek

c. San Pedro River

- i. Brand LA, JC Stromberg, BR Noon. "Avian density and nest survival on the San Pedro River: importance of vegetation type and hydrologic regime." Journal of Wildlife Management. In press (May, 2010, expected).

d. Verde River

- i. USGS and TNC. "Establishing environmental flows for sustainable water management: Upper and Middle Verde River watersheds, Arizona" Ongoing.

3. Impacts of changing flows on riverine and riparian ecosystems
 - a. Santa Cruz River
 - i. Villarreal, M. L., W.J.D. vition with reIndicators. Submitted, In Review
 - ii. Villarreal, M. L., Drake, S., Marsh, S.E and A.L. McCoy. 2010. "The influence of wastewater subsidy, flood disturbance and neighboring land use on current and historical patterns of riparian vegetation in a semi-arid watershed." Ecosystems. Submitted, In Review
4. Valuation of Riparian Ecosystems
 - a. Brookshire et al. (forthcoming). Analysis of valuation surveys.
5. Water Quality issues
 - a. Quanrud, D.; C. Propper. 2010. "Wastewater Effluent: Biological Impacts of Exposure and Treatment Processes to Reduce Risk. A literature review prepared for The Nature Conservancy in Arizona."
 - b. White, M. 2010. "Effluent-Dependent Waterways in the Southwest: Advancing Water Policy through Ecological Analysis."