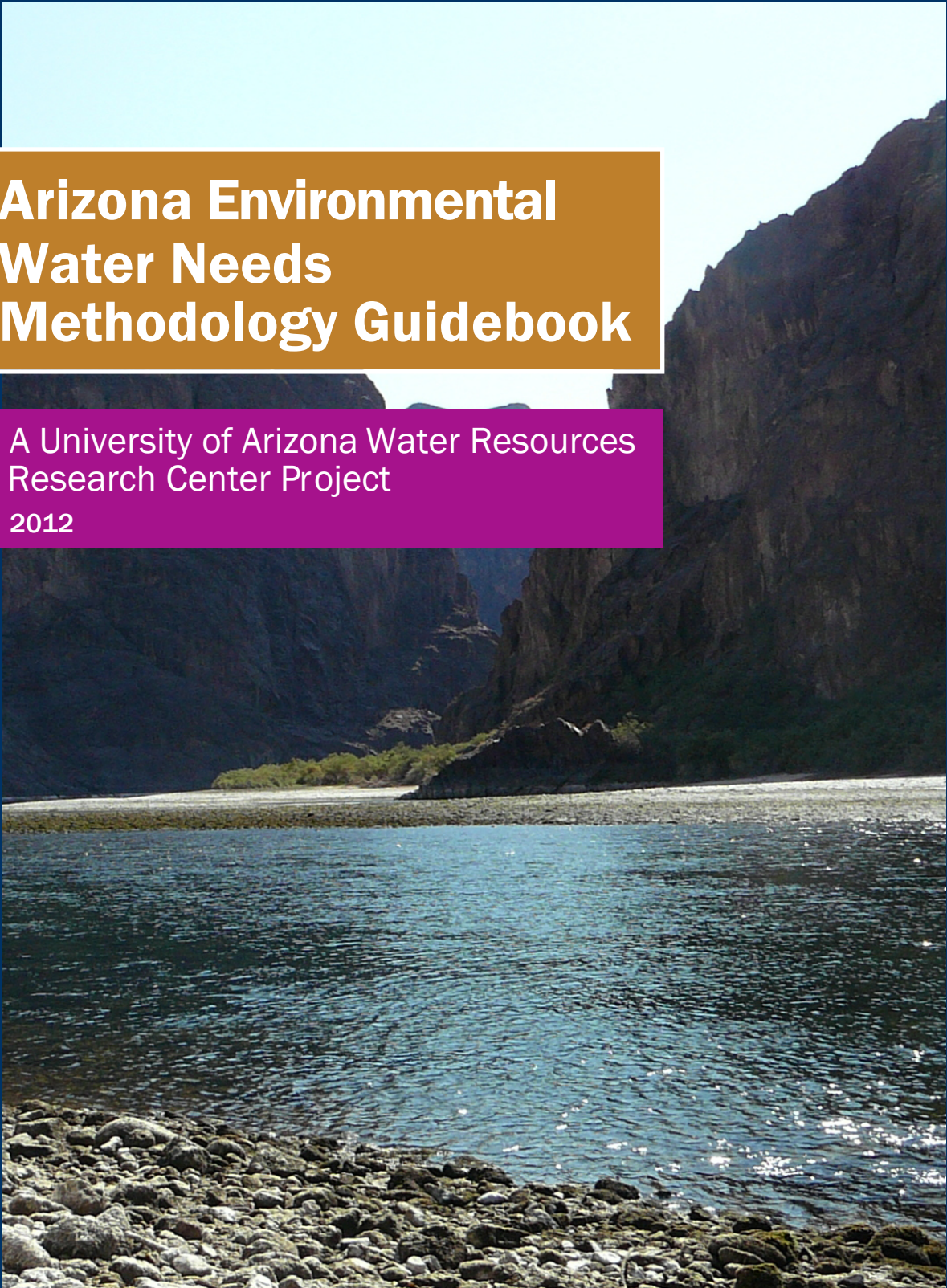




COLLEGE OF AGRICULTURE
AND LIFE SCIENCES

Arizona Environmental Water Needs Methodology Guidebook

A University of Arizona Water Resources
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Arizona Environmental Water Needs Assessment Report

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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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I. INTRODUCTION

Determining the best methods for quantifying environmental flow needs depends on what is to be studied as well as how the information will be used. The perspective of the scientist studying the environment will influence their impression of what water it needs. The hydrologist is likely to find hydrological methods most substantial, the vegetation ecologist will look for correlation between riparian (bank side) trees and surface water presence. The water manager wants a study that addresses their concerns about the watershed. But make no mistake: the environment is very complex, and its functionality depends on the health and integrity of all of its parts.

When tasked with the job of coming up with an environmental flow prescription or instream water right, it is best to look at the complexity by incorporating a variety of perspectives. Using aquatic (in-stream) methods alone might overlook relationships between surface water and riparian birds and, conversely, managing water for cottonwood trees might not leave enough for Arizona's imperiled snails. In general, the more tools and techniques that are used to quantify the ecosystem water parameters, the better. The use of a diverse panel of experts to develop broad goals for riparian ecosystems is also a good option. When the methodologies used to quantify ecosystem services consider flow needs holistically and are coupled with stakeholder and expert opinions, the solution is most likely to be ecologically sustainable and supported by a consensus.



Black Phoebe, Cienega Creek. Photo Credit: Audrey Nelson

The challenge that remains is in trying to piece together the information we do have into something that can be used in decision making. We already know the nature of the problem: declining flows in Arizona's rivers have adverse consequences for our state's ecological health. Numerous studies have been conducted in the San Pedro River documenting the effects of declining groundwater tables, reduced streamflow and flooding, as well as the impact of hydrologic alterations on mammal, vertebrate, avian, and vegetation species. And yet the total amount of water necessary to sustain all the organisms in the San Pedro riparian ecosystem has not been established. To determine what we know requires understanding the tools used to create that knowledge and the tools needed to fill in the gaps.

Check the glossary (Appendix A) for definitions of any unfamiliar terms.

PURPOSE OF GUIDEBOOK

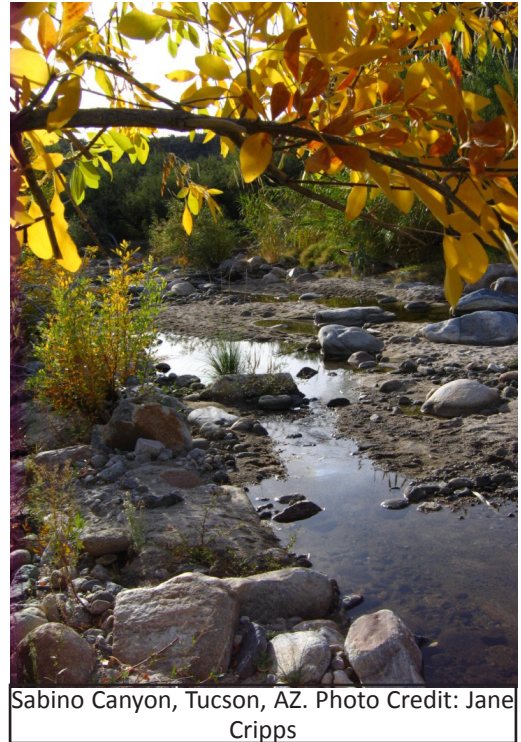
This guidebook will provide a description of the methodologies used in Arizona to define the environment's need for water. Depending on the geographic context, the time and effort available, and whether the goal is restoration or maintenance of an ecosystem, some methods will be more appropriate for a given application than others. The resulting flows prescribed by each method may be more or less feasible when paired with socio-political considerations or water availability. The goal of this guidebook is to help the reader navigate new territory, to illuminate the various points of contact and the corresponding issues they address.

II. OVERVIEW OF METHODOLOGIES USED IN ARIZONA'S ENVIRONMENTAL WATER NEEDS STUDIES

HOW ARE STUDIES DONE?

Quantifying environmental water needs is an emerging and an evolving science (Richter et al. 2003, 206-224): 83 of 93 studies in our inventory were published since 2000. Several papers describe the range of methods used in environmental flows science (Poff et al. 1997, 769-784; Richter et al. 2003, 206-224; Katz 2006, 29-49). Various approaches can be taken to determine not only the amount of water but also the temporal and spatial patterns of water flow that sustain aquatic and riparian biotic communities (Stromberg et al. 2009a, 371). Approaches for determining environmental water needs have expanded over time from narrowly considering minimum instream flow needs to addressing the whole river corridor and many components of a flow regime (Petts 2009, 1071-1086).

Research about environmental water needs can be done in different ways. The hydrological context provides a first cut in distinguishing methods, and therefore, studies. Researchers may study the flow needed to maintain a healthy aquatic ecosystem, a healthy riparian area, or both. Sometimes researchers rely on historical flow patterns of a river to define its flow needs; other times they use present-day observations to identify relationships between ecological components and the 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. The most recent innovation is environmental flows (e-flows) studies that incorporate societal values into flow prescriptions (Katz 2006, 29-49; Tharme 2003, 397-441).



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

Table 1. Methods Classification

Qualitative Methods	
Distribution of flora and fauna associated with water sources	
Flow-ecology response curves	
Flow-ecology response relationship described	
Quantitative Methods	
Aquatic	Riparian
Hydrological index	Hydrological event models
Hydraulic rating	Water budget/Evapotranspiration
Habitat simulation	Water source
Biological response to flow	Eco-flow response curves
correlation	Biological event models
Holistic	

Increasing complexity
↓
↓
↓
↓
↓

In order to make sense of the various methods, we created a classification system (Table 1). Though useful for describing methods generally, published literature reviews differ widely in their approach to classifying them. Our classification focuses primarily on the type of data used to define flow needs in Arizona, following approaches used by Tharme et al. (2003) and Petts (2009). Methods that used both biological and hydrological data were distinguished from those that used hydrological data as a substitute for data on biological needs. We also stratified methods according to the hydrological context in which they were applied, as well as the method's ability to provide quantitative results.

The literature classifying and evaluating aquatic and holistic methods is much more extensive than that of riparian methods, so we used an approach combining expert input and published literature to finalize our riparian classification. Arthington and Pusey (2003), Glenn et al. (2007), and Merritt et al. (2010) were important guides for classifying the riparian methods. The riparian classes mirror the aquatic methods classes: both sets start with hydrology-based methods and move through increasing complexity to methods correlating flow elements with biological indicators. At the most complex level, some studies use holistic methods, which incorporate both aquatic and riparian elements. Finally, several qualitative methods emerged from our inventory to describe ecological-flow relationships.

Biological- *Of or relating to life or living things.*

Hydrological- *Of or relating to the properties, distribution, and effects of water on the earth's surface, in the soil, and in the atmosphere.*

FIELD DATA, EXPERT INPUT

Forty-two studies collected new field data as part of their investigation. Sixty studies utilized existing data to do their analysis. Eight studies from the Arizona inventory enlisted a team of experts in a decision process to define flows, or flow-related management objectives (Dwire et al. 2008, 49; Haney et al. 2008, 114; Hautzinger et al. 2006, 71; Shafroth and Beauchamp 2006; Stevens, Turner, and Supplee 2008, 51; Turner and Haney 2008; U.S. Fish and Wildlife Service 1989, 132).

The companion Arizona Environmental Water Needs Assessment Report has a discussion of study findings and important distinctions between studies of flow needs and flow responses.

E-Flow Methods At a Glance

Aquatic E-flow Methods address in-stream elements

- **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 address river bank or terrace elements

- **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 address both aquatic and riparian elements

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

III. EVALUATION OF METHODOLOGIES

EVALUATION APPROACH

Taking our methods classification scheme, we performed a literature search for the methods used in Arizona water needs studies (Table 1). Our Advisory Committee assisted us in selecting criteria that would be relevant to decision makers to use in evaluating the methods. The published literature was then used to evaluate methods on the chosen criteria (Richter et al. 2003, 206-224; Katz 2006, 29-49; Petts 2009, 1071-1086; Tharme 2003, 397-441; Arthington and Pusey 2003, 377-395; Glenn et al. 2007, 139-168; Merritt et al. 2010, 206-- 225; Arizona Department of Water Resources 1991, 34; Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Poff et al. 2003, 298-306; Annear et al. 2004; Poff and Zimmerman 2010, 194-205). Some methods, mainly the newer ones, have not been evaluated as extensively in the literature as others. Where methods lack evaluative data, we have not attempted to fill in the blanks. See Appendix D for the complete Methods Evaluation Table.

Eighteen of 93 studies provided little description of methods used therein. Thus, some additional methods may have been used that are not reported here. Methods that have not been used in any Arizona studies are not evaluated in this guidebook or used in the decision tree, but are included in the science process chart. If you are not familiar with these methods, you may want to read Section IV first to familiarize yourself with the methods discussed in this evaluation section.

DECISION TREE FOR SELECTING METHODOLOGY

Based on information gathered from the methods evaluation, a decision tree (Figures 1-3) has been created to assist with:

- 1) Finding published studies using appropriate methods to guide management for a specific situation, and
- 2) Finding methods that would be appropriate to answer specific management question(s).

HOW TO USE THE DECISION TREE

Choosing a methodology requires knowing what each method can produce, and then selecting a method that is appropriate for your situation. The decision tree does this work for you, by using information about each criterion to direct you to the relevant method(s). Each criterion has been phrased as a question that you can apply to your management situation. By following the pathway (lines) down the page, you will be directed to certain classes of methods and specific method types that match your answers. Due to the size of the decision tree, the first question about hydrological context options is separated into three pages: aquatic, riparian, or holistic.

DISCUSSION ABOUT CRITERIA USED

HYDROLOGICAL CONTEXT

Basic guidance: Answer this question based on the hydrological context of the living things that this decision/study concerns. Aquatic taxa include fish, macroinvertebrates, amphibians, and some mammals, insects and reptiles. Riparian taxa include plants, birds, some mammals and arthropods, and most reptiles.

Discussion: Ideally, every management decision or study regarding environmental water needs would consider the aquatic and riparian elements of the ecosystem in tandem, because they are truly interconnected. However, some circumstances involve decisions being made or stressors being introduced that are likely to affect certain ecosystem elements more than others. Or, resources are limited, so the inquiry must be restricted to a set of species of concern. Thus, some methods will be more appropriate for a given hydrological context than others.

Question 1 of the decision tree is: “What is the hydrological context of interest?”

Your options:

Aquatic – Figure 1

Riparian – Figure 2

Holistic – Figure 3

FIGURE 1. DECISION TREE – AQUATIC CONTEXT

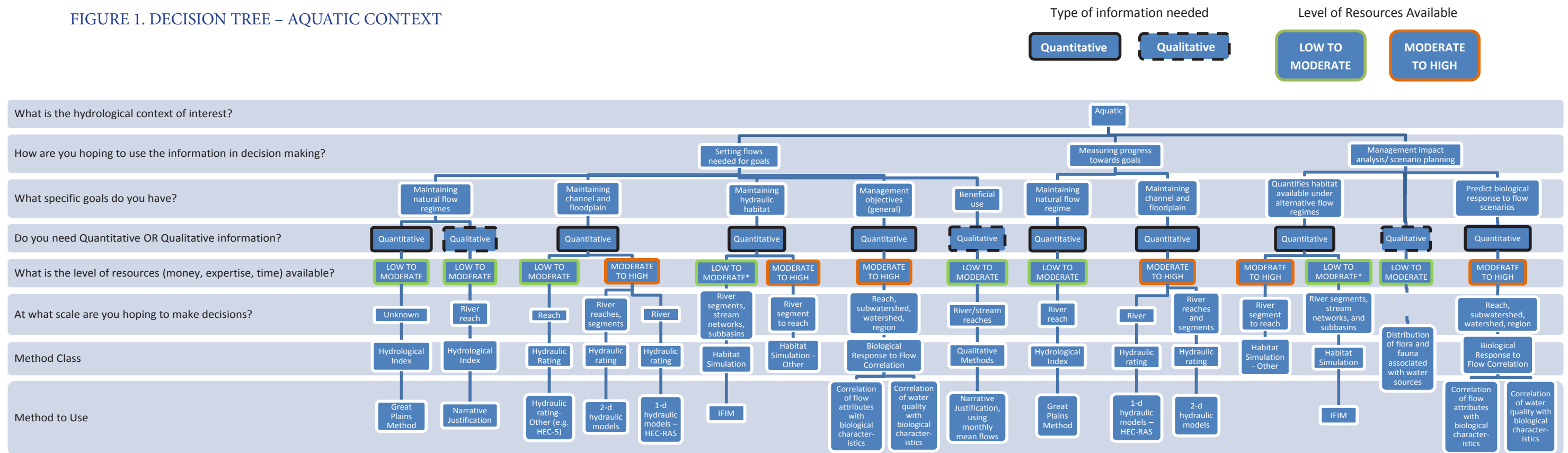


FIGURE 2. DECISION TREE – RIPARIAN CONTEXT

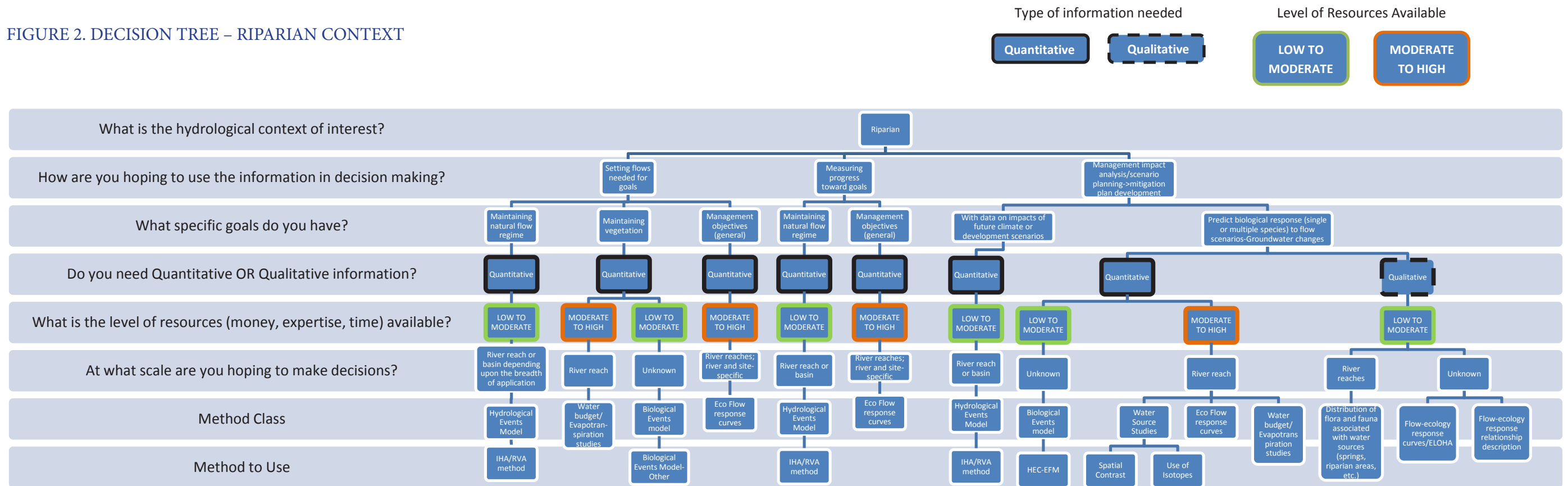
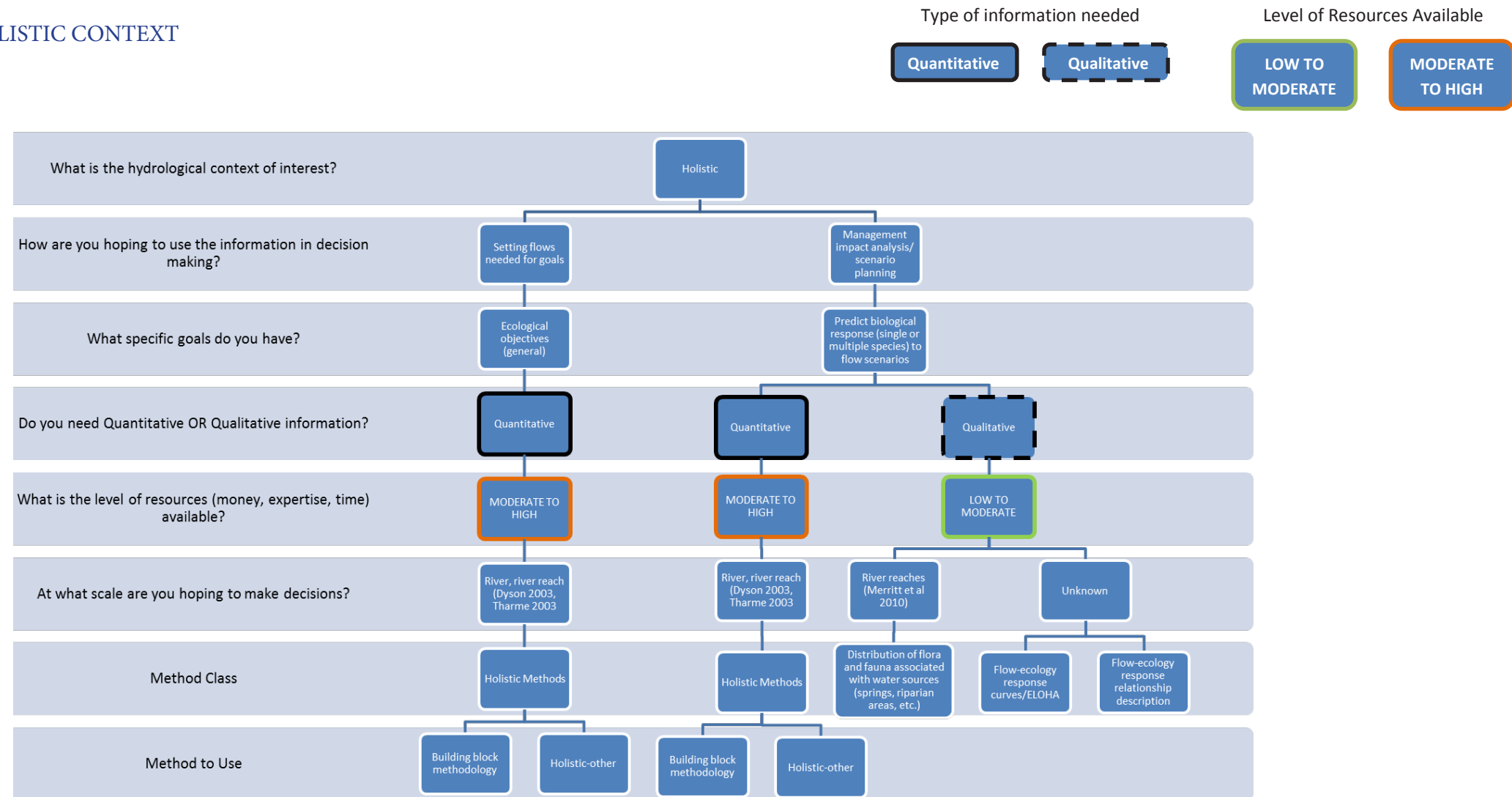


FIGURE 3. DECISION TREE – HOLISTIC CONTEXT



USE/PURPOSE FOR POLICY/DECISION-MAKING

Basic guidance: Answer this question based on how this method/study should address decision making needs.

Discussion: It should be noted that while some methods can be applied to both setting and measuring the progress of conservation or restoration goals, many methods are not designed to serve these dual purposes. For example, the narrative justification method can be used to set flows needed for beneficial use by fish and wildlife, but will not necessarily be useful in measuring progress toward achieving those flows. When determining a method's use or purpose for policy/decision making, this Guidebook has classified the methods by their intended use. Based on the literature, there are a smaller number of methods available for measuring progress towards conservation or restoration goals than are useful for setting flows for such goals.

An additional note for discussion: hydraulic rating methods, when used alone, are most useful in defining and measuring flows needed for channel and floodplain maintenance, as noted in the decision tree. Studies in this inventory only ever used the hydraulic rating methods in conjunction with other methods that link flow to ecology, in part because the focus of this assessment was to identify the water needs of living things. Thus, you will not find typical hydraulic studies in our list of studies by method, but rather those that build off of hydraulic information.

Questions 2 and 3 of the decision tree are: “How are you hoping to use the information in decision making?” and “What specific goals do you have?”

Your options:

1. Setting flows needed for conservation or restoration goals
 - a. Maintaining natural flow regime
 - b. Maintaining channel and floodplain
 - c. Maintaining hydraulic habitat (e.g. for fish)
 - d. Maintaining vegetation
 - e. Beneficial use
 - f. Other ecological objectives
2. Measuring progress towards conservation or restoration goals
 - a. Maintaining natural flow regime
 - b. Maintaining channel and floodplain
 - c. Other ecological objectives
3. Management impact analysis/scenario planning/mitigation plan development
 - a. Quantifies habitat available under alternative flow regimes
 - b. Predict biological response to flow scenarios

QUANTITATIVE/QUALITATIVE

Basic guidance: Answer this question based on whether you require quantitative (numeric) results from the study, or whether qualitative (descriptive) information could be useful.

Discussion: Methods that provide quantitative information about environmental water needs may prove useful to decision making where specific flow levels or impacts are of interest. Qualitative methods that describe ecological-flow relationships in non-quantitative terms may be used to state hypotheses about management that can be tested or identify locations of species of concern.

Question 4 of the decision tree is: “Do you need Quantitative OR Qualitative information?”

Your options:

Quantitative

Qualitative

COST/EFFORT REQUIRED

Basic guidance: Answer this question in terms of the resources you have available for a study, including time, money, expertise, and data. Note: if you are using the decision tree to find studies that are relevant to your situation, this question may not be useful.

Discussion: These methods vary in terms of the time, information, and expertise that they require. We used a relative, qualitative scale to characterize the resources needed for each method. Generally, methods that require more time and information also require financial resources and technical expertise to complete. “Moderate to high” methods will involve more costly inputs such as field work, site-specific data analysis, and requires skilled expertise. Similarly, methods that are quick and easy are often less expensive as well. “Low to moderate” methods have established manuals or software available for use, and often rely on desktop analysis of existing data in lieu of field work. Additional details about **this criterion are provided for each method in the Methods Evaluation Table (Appendix D).**

Question 5 of the decision tree is: “What is the level of resources (money, expertise, time) available?”

Your options:

Low to Moderate

Moderate to High

SCALE

Basic guidance: Answer this question according to the various locations or scales at which you would like to have information about environmental water needs.

Discussion: Most of the methods produce results that are intended for use at the river segment/reach scale (i.e. not the full extent of a river). A few can be applied across stream networks or from river to river. See the Transferability section for further discussion of this issue.

Question 6 of the decision tree is: “At what scale are you hoping to make decisions?”

Your options:

River segment

River reach

River

Subwatershed or Sub basin

Watershed or River basin or Stream network

Region

Subwatershed- smaller unit of a watershed.

Watershed/River Basin-the area of land where all of the water that is under it or drains off of it goes into the same place.

YOUR RESULT

Each pathway leads to a method class - and the specific method type in that class - that matches your answers. This resulting method, and studies that have used this method, will be most appropriate for your management situation.

A list of studies that have used each method is located in Appendix B. Further detail about the methods is located in Section IV. This additional detail includes the type of data required, the quality of outputs (Strengths), the limitations and weaknesses of each method, and the use of the method's findings in other systems. In some cases, more detailed information about these methods is not available, in which case the list will say "unknown."

TRANSFERABILITY: THE USE OF FINDINGS IN OTHER SYSTEMS

The Arizona Environmental Water Needs Assessment Report (companion document) determined that some river basins in Arizona are much more extensively studied than others. Because little research has been done in some basins, identifying rivers with similar characteristics could help in filling in these research gaps, as data from one river can sometimes be extrapolated to another. For example, several studies from the Arizona inventory used data from other river basins to develop hypotheses or predictive models (Springer et al. 1999, 3621-3630; Haney et al. 2008, 114).

The findings produced offer insights about the system where they were applied, but the question remains: can any of these methods provide findings that apply more broadly to under-studied rivers in the region? Highly specific data about a river reach generally will not be applicable to a different system. When hydrographs or flow curves are developed from gaged sites, they cannot be directly extrapolated to ungaged sites or other points on the stream without calibration (Locke et al. 2008).

Gaged Site- has historical record of flow for that point in a stream or river.

Methods that rely on lookup (or reference) tables or simple indices can only be applied to rivers in the region where they were developed (Dyson, Bergkamp, and Scanlon 2003, 118 pp.). Empirical regression approaches (e.g. biological correlation with flow methods) cannot be directly transferred to other river basins (Merritt, Bateman, and Peltz 2010, 85). In most cases, indices need to be recalibrated before they are applied to new regions or rivers.

On the other hand, several methods explicitly aim to be transferable between similar ecosystems. These include habitat models that are developed for a region that can be transferred between rivers of similar type (Petts 2009, 1071-1086). However, Annear (2004) cautions that flow recommendations from habitat models should be adjusted to the hydrological characteristics of each river, since they are a function of flow and channel shape (Annear et al. 2004). Also, the ELOHA method provides guidance in classifying rivers to reduce the need for unique studies on every river (Poff and Zimmerman 2010, 194-205). Merritt et al. (2010) affirms this approach to making generalizations, offering riparian vegetation-flow response guilds as a mechanism for transferring information from river to river. In any case, extrapolating data is necessarily an imperfect science, but available studies can provide starting points for discussion and consideration in water management.

SCIENCE PROCESS CHARTS

Science process charts have been developed to demonstrate how one type of study might feed into another, and vice versa (Figure 4). The following tables outline the required/suggested informational inputs and the outputs generated by each method class.

These charts will help determine appropriate next steps for research, as well as potential sources of information when undertaking certain study methods. Each of the eleven method classes used to describe e-flows studies can be connected to at least one other method class. This is because information required for one study often lays the foundation for a more advanced study of the same location. The information needed for the science process chart was developed through the same methods evaluation as the decision tree (see Appendix D. Methods Evaluation Table). Information was collected from the literature specifically about the data required to complete each method and the uses of the information produced by each method for the science process.

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For help interpreting the table, consider this example: results from a study using Indicators of Hydrological Alteration (a Hydrological Index method) can be used in the ELOHA process (a Holistic method) regardless of whether the original data have an aquatic or riparian focus. The same is true for ecological-flow response curves and biological flow response correlations, which can be done on aquatic and riparian elements. More detail about the uses of each method is included in its detailed description in the next section.

Figure 4. Science Process Chart (Inputs and Outputs)

X=Required Input for Method Class		X=Not Required, May Improve Data									
Input Required		Method Class									
	Hydrological Index	Hydraulic Rating	Habitat Simulation	Biological Response from Flow	Hydrological Event Model	Water Budget/ET Studies	Water Source Studies	Eco-Flow Response Curves	Biological Event Model	Holistic Methods	Non-Quantitative Methods
Hydrologic Records	X	X	X	X	X		X	X	X	X	
Hydraulic Model							X		X	X	
Habitat Simulation											X
Hydrological Event Model											X
GIS/Remote Sensing Data						X			X	X	X
ET Data						X	X				
Isotope Levels							X			X	
Biological Response Data	X	X	X	X		X	X	X	X	X	X
In-situ Observations	X	X	X	X	X	X	X	X	X	X	X
Expert Input		X								X	X

X=Consistent Output for Method Class		X=Occasional Output for Method Class									
Output Generated		Method Class									
	Hydrological Index	Hydraulic Rating	Habitat Simulation	Biological Response from Flow	Hydrological Event Model	Water Budget/ET Studies	Water Source Studies	Eco-Flow Response Curves	Biological Event Model	Holistic Methods	Non-Quantitative Methods
Environmental-Flow Hypotheses		X		X		X	X	X	X		X
Flow Variation	X				X						
Spatially Explicit Data		X	X			X	X		X	X	
Habitat Flow Relationship	X		X				X	X	X	X	X
Hydrologic Classification					X						

V. METHODS DATABASE AND SUMMARY

METHODS DEFINITIONS

This section provides a basic definition for each method discussed in this Guidebook, along with information from the literature about the data required, quality of output (strengths), limitations and weaknesses of each method, and the use of findings in other systems. The depth of information provided here depends to some extent on how well-known each method is. Thus, some newer methods may appear to have fewer limitations, when in fact their limitations are not yet known.

A. AQUATIC METHODS

In terms of **aquatic, quantitative** methods, the following methods have been used in Arizona or are commonly referred to in the methods literature:

a. HYDROLOGICAL INDEX

Hydrological Index methods rely on hydrological data (naturalized or historical monthly or daily flow records) to make environmental flow recommendations (Tharme 2003, 397-441). This includes the Great Plains method, Narrative Justification method, the Richter method/ Range of Variability Approach (RVA), and the Indicators of Hydrological Alteration (IHA) Method. The last two methods in this class are not known to be applied in Arizona (i.e. used in any of the inventoried studies), but are commonly cited in the literature.

The **Great Plains method** describes hydrological conditions for each specific month and for dry periods based on flow records, involving a flow duration curve based on a 90% exceedance value from all years of record.

Data Required: Daily hydrographs from a period of record

Quality of Output/Strengths: Provides satisfactory preservation flows, for most fish species; can be used to analyze general habitat for fish, wildlife and recreation; developed largely for streams with highly seasonal flow patterns, and monthly flows are assessed to incorporate this variability (Tharme 2003, 397-441)

Limitations and Weaknesses: Best used when prior data exist and needs field testing in different regions of the USA; some elements of EFR are based on professional opinion; should only be applied to rivers with similar morphology as where developed; does not include most extreme year types (Tharme 2003, 397-441)

Use of Findings in Other Systems: Unknown

The **narrative justification method** uses monthly mean flows to provide a summary of hydrologic data and description of e-flow relationships (Arthington and Pusey 2003). Figure 5 provides an example of mean monthly average discharge (dark blue horizontal line) combined with the maximum mean monthly average for period of record (top of vertical blue line) and minimum mean monthly average for period of record (bottom of vertical blue line; Briggs 2008).

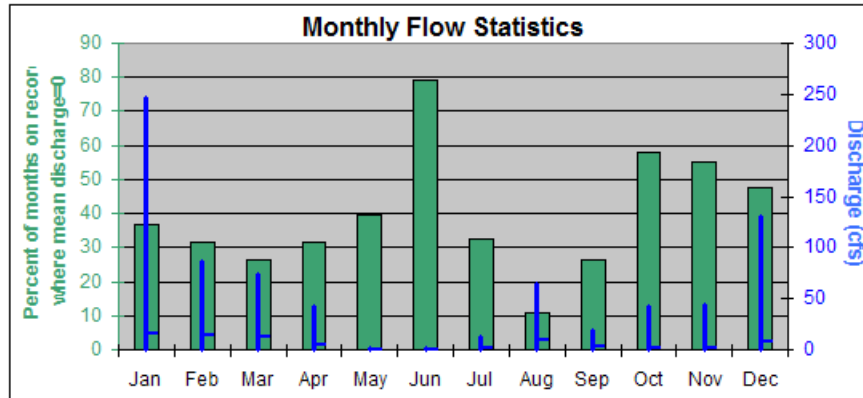
Data Required: Documentation of preexisting hydrologic records: monthly mean flows (Arizona Department of Water Resources 1991, 34)

Quality of Output/Strengths: “The primary use of this method is for...streams where there is little or no controversy or challenge and where no increase in consumptive use is anticipated. However, because the method will save considerable time, effort, and money...this method acceptable when used in appropriate circumstances.” (Arizona Department of Water Resources 1991, 34)

Limitations and Weaknesses: Dependent on available hydrologic data, dependent on judgmental expertise; used mostly for conflict-free areas (Arizona Department of Water Resources 1991, 34)

Use of Findings in Other Systems: Unknown

Figure 5. Mean Monthly Flows



The **Richter method/ Range of Variability Approach (RVA)** defines benchmark flows in need of river management by identifying an “appropriate” range of variation of flows based on five components: (1) magnitude of flow, (2) timing of flow, (3) frequency of various flow events, (4) duration of flow events, and (5) rate of change between types of flows (Annear et al. 2004; Katz 2006, 29-49). This method has not been used in Arizona on aquatic systems, but is commonly applied elsewhere.

Data Required: Existing river flows; existing fish data can improve outputs; daily records or supplementary field data (Dyson, Bergkamp, and Scanlon 2003, 118 pp.)

Quality of Output/Strengths: Intended to maintain integrity, natural seasonality, and variability of flows (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); high quality requires consideration of anthropogenic alteration of streamflow, sediment dynamics (Petts 2009, 1071-1086)

Limitations and Weaknesses: Flow statistics have not been related to specific ecological elements (Dyson, Bergkamp, and Scanlon 2003, 118 pp.)

Use of Findings in Other Systems: Unknown

The **Indicators of Hydrological Alteration (IHA)** method – tool to characterize inter-annual variation for a set of hydrologic parameters in order to evaluate and quantify changes in hydrologic regimes (Annear et al. 2004; Petts 2009, 1071-1086). This method has not been used in Arizona on aquatic systems, but is commonly applied elsewhere.

Data Required: Daily natural flow records (Annear et al. 2004); can select parameters based on local circumstances (Petts 2009, 1071-1086)

Quality of Output/Strengths: Offers range of variability for indicators (Tharme 2003, 397-441); high quality requires consideration of anthropogenic alteration of streamflow (Petts 2009, 1071-1086)

Limitations and Weaknesses: Does not address physical or biological characteristics directly such as life history flow events (Annear et al. 2004; Katz 2006, 29-49); ecological validity uncertain (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); needs to incorporate riparian requirements (Richter 2006); assumes coverage of inter annual variation by intra annual variation (Annear et al. 2004)

Use of Findings in Other Systems: Unknown

b. HYDRAULIC RATING

Hydraulic rating methods use changes in hydraulic variables as a surrogate for habitat factors thought to be important to biota (Tharme 2003, 397-441). This includes one-dimensional hydraulic models (such as HEC-RAS), two-dimensional hydraulic models, and other hydraulic rating methods.

The **one-dimensional hydraulic models**, such as HEC-RAS, create a water surface profile model that recommends flows necessary for channel and floodplain maintenance (Annear et al. 2004).

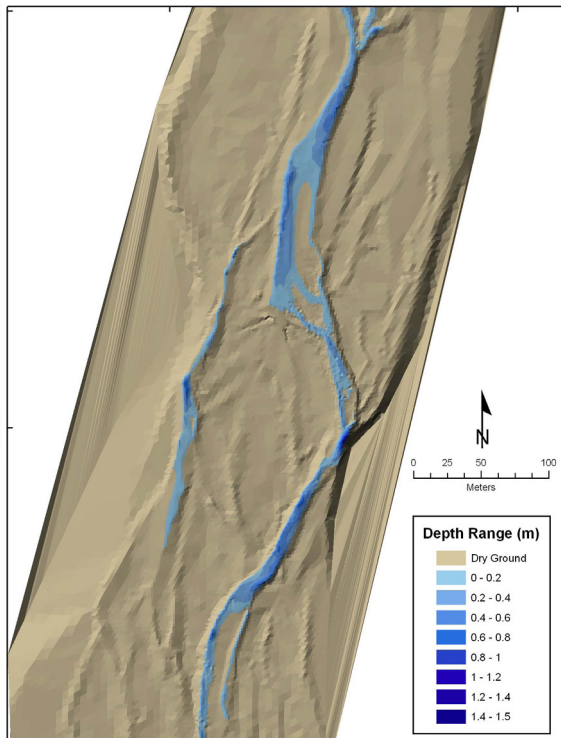
Data Required: Hydraulic parameters (Arizona Department of Water Resources 1991, 34)

Quality of Output/Strengths: Produces spatially explicit predictions (Shafroth et al. 2010, 68-85)

Limitations and Weaknesses: Lack of data reduces reliability, critical site classification subjective (Arizona Department of Water Resources 1991, 34); requires additional development of links between physical processes and ecosystem benefits (Annear et al. 2004); not appropriate for high-gradient streams and rivers (Annear et al. 2004)

Use of Findings in Other Systems: Unknown

Figure 6. Hydraulic Model of a Stream



The **two-dimensional hydraulic models** are computer models used for simulating patterns in a stream (elevation, velocity, and depth) and may be linked with other models to simulate unmeasured discharges (Annear et al. 2004). Figure 6 provides an example of the output from a hydraulic model of water depth in a stream (Waddle and Bovee 2009).

Data Required: Hydraulic parameters and composite graphs (Arizona Department of Water Resources 1991, 34)

Quality of Output/Strengths: Decent analytical capabilities, model predictions provided (Arizona Department of Water Resources 1991, 34)

Limitations and Weaknesses: Cannot relate habitat to fish biomass; useful for determining “flow data for ungaged streams” but not considered a “substitute for on-site streamflow measurements” (Arizona Department of Water Resources 1991, 34)

Use of Findings in Other Systems: Unknown

Other hydraulic rating methods use changes in hydraulic variables as a surrogate for habitat factors thought to be important to biota.

Data Required: Desktop analysis of field surveys or river gauging data (Dyson, Bergkamp, and Scanlon 2003, 118 pp.)

Quality of Output/Strengths: Produces spatially explicit predictions (Shafroth et al. 2010, 68-85)

Limitations and Weaknesses: Disregards biological information and natural flow variation (Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Katz 2006, 29-49); requires additional development of links between physical processes and ecosystem benefits (Annear et al. 2004); assumptions are made that hydraulic variables can be surrogate for habitat factors (Tharme 2003, 397-441); unreliable if based on single expert (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); subjective determination of site selection weakens EFRs (Dyson, Bergkamp, and Scanlon 2003, 118 pp.)

Use of Findings in Other Systems: Only at study site (Dyson, Bergkamp, and Scanlon 2003, 118 pp.)

c. HABITAT SIMULATION

Habitat simulation methods analyze quantity and suitability of instream habitat for key species available under different discharges/flows to determine habitat-discharge curves (Tharme 2003, 397-441; Katz 2006, 29-49). Habitat-discharge curves provide graphical representation of relationships between stream discharge (or volume rate of water flow) and habitat variables. This includes the Instream Flow Incremental Methodology and other habitat simulation methods.

The **Instream Flow Incremental Methodology (IFIM)** links hydraulic simulation with habitat evaluation criteria for species and life stages (Petts 2009, 1071-1086) and integrates flow-related changes in habitat with preferred habitat conditions for selected species to predict or avoid impacts from flow changes. Figure 7 demonstrates the habitat suitability curves that resulted from an IFIM analysis for the desert sucker (U.S. Fish and Wildlife Service 1989, 132).

Data Required: Site-specific, high-quality field data, life history information, hydrologic models (Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Annear et al. 2004; Petts 2009, 1071-1086); PHAB-SIM information, IFIM data analysis program (Arizona Department of Water Resources 1991, 34)

Quality of Output/strengths: Output quality determined by HSI quality (Petts 2009, 1071-1086); integration of models allows for spatial and temporal relationships of habitat to water management (Annear et al. 2004); best method to quantify habitat flow relationships (Arizona Department of Water Resources 1991, 34)

Limitations and Weaknesses: Lack of concordance between changes in suitable habitat and fish populations, simplified approach to hydraulic habitat characterization, and lack of biological realism (Petts 2009, 1071-1086); lack of ecological predictive capacity (Tharme 2003, 397-441); uncertainty often not addressed (Dyson, Bergkamp, and Scanlon 2003, 118 pp.)

Use of Findings in Other Systems: Unknown

Other habitat simulation methods analyze quantity and suitability of instream habitat for key species available under different discharges/flows to determine habitat-discharge curves.

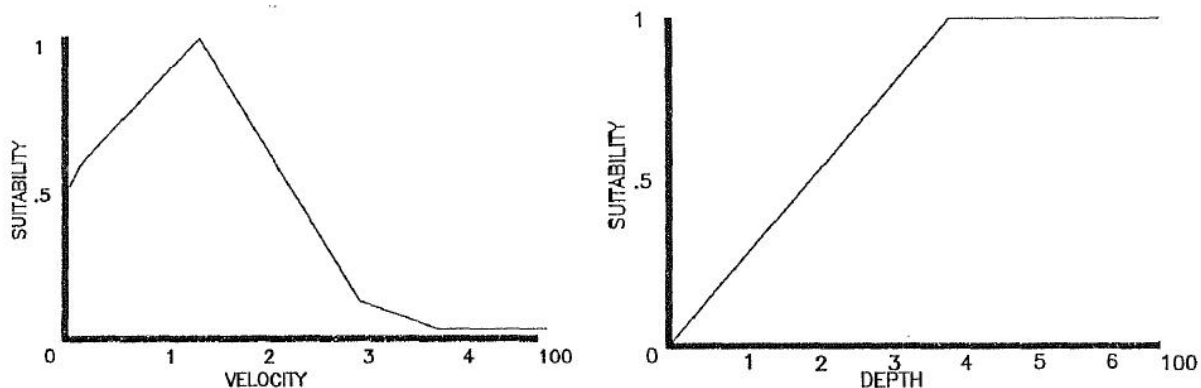
Data Required: Site-specific data, habitat suitability representations (Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Annear et al. 2004)

Quality of Output/Strengths: Replicable, predictive (Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Katz 2006, 29-49)

Limitations and Weaknesses: Need to study habitat persistence to address abundance/reproduction (Locke et al. 2008)

Use of Findings in Other Systems: May allow regional transfer of habitat use models among rivers of similar type (Petts 2009, 1071-1086) or may require stratified sampling to extrapolate from reaches to segments (Annear et al. 2004)

Figure 7. Habitat Sustainability Curve



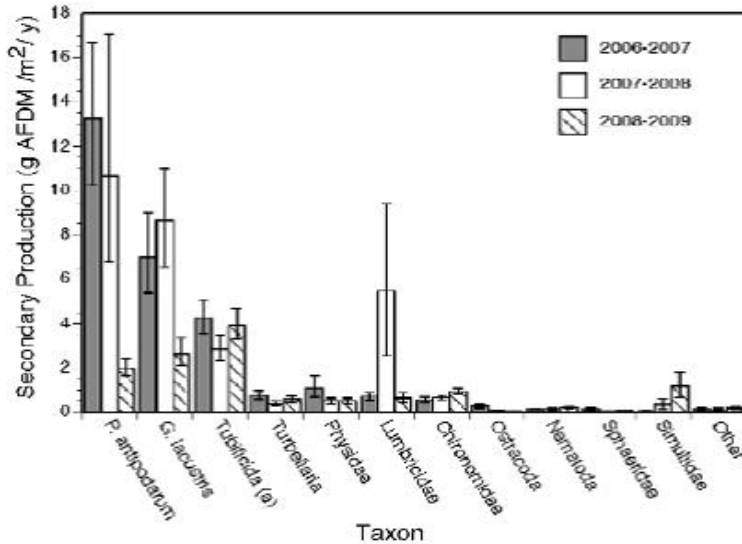
d. BIOLOGICAL RESPONSE TO FLOW CORRELATION

Biological response to flow correlation methods establish a relationship between data on biological or habitat quality indicators and a flow related variable (Annear et al. 2004). This includes methods correlating flow attributes such as magnitude and timing and water quality with biological characteristics.

Correlation of flow attributes (e.g. magnitude and timing) **with biological characteristics and correlation of water quality with biological characteristics** (Annear et al. 2004). Figure 8 shows macroinvertebrate species dynamics before and after a high flow event (Rosi-Marshall et al. 2010).

Data Required: Several years of data on biological variables, flow attributes (Annear et al. 2004); data collected for other purposes may not be suitable (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); statistical techniques may require independent time series of flow and ecological indices (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); discharge, temperature and dissolved oxygen need to be studied if water quality may change (Locke et al. 2008)

Figure 8. Macroinvertebrate Growth Before and After a Flow Event



Quality of Output/Strengths: Addresses flow and ecology (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); directly accounts for river characteristics (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); data quality relies on sample size, statistical power (Annear et al. 2004)

Limitations and Weaknesses: Does not capture all (i.e. non-flow related) sources of variability affecting biological response; provide general relations and trends and not much indication of tight estimates of population or habitat metrics (Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Annear et al. 2004)

Use of Findings in Other Systems: Determine stream type similarity to stream used to develop model before extrapolating; should be tested first (Annear et al. 2004; Dyson, Bergkamp, and Scanlon 2003, 118 pp.)

B. RIPARIAN METHODS

In terms of riparian, quantitative methods, the following methods have been used in Arizona or are commonly referred to in the methods literature:

a. HYDROLOGICAL EVENT MODEL

Hydrological event models depict natural flow regimes assumed to benefit ecological functions/elements (how flows affect water table, overbank flows, stream margins). These include the Indicators of Hydrological Alteration (IHA) method and the Range of Variability Approach (RVA) method.

Indicators of Hydrological Alteration (IHA) method and the Range of Variability Approach (RVA) method are tools that characterize inter-annual variation for a set of hydrologic parameters in order to evaluate and quantify changes in hydrologic regimes (Richter et al. 2003, 206-224).

Data Required: Requires daily natural flow records (Annear et al. 2004); can select parameters based on local circumstances (Petts 2009, 1071-1086)

Quality of Output/Strengths: Offers range of variability for indicators (Tharme 2003, 397-441); high quality requires consideration of anthropogenic alteration of streamflow (Petts 2009, 1071-1086)

Limitations/ Weaknesses: Does not address physical or biological characteristics directly such as life history flow events (Annear et al. 2004; Katz 2006, 29-49); ecological validity uncertain (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); assumes coverage of inter-annual variation by intra-annual variation (Annear et al. 2004)

Use of Findings in other Systems: Unknown

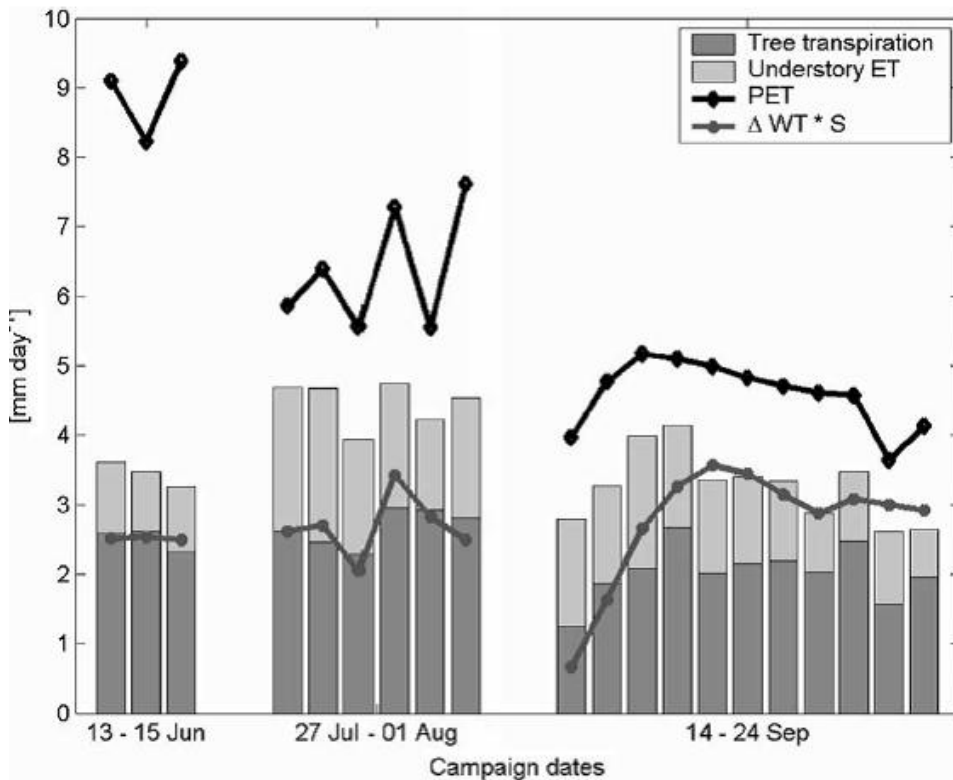
b. WATER BUDGET/EVAPOTRANSPIRATION STUDIES

Water budget/Evapotranspiration studies are remote sensing studies of plant water use that predict water needs at landscape scales. Figure 9 shows total daily evaporation from a mesquite ecosystem (total bar height) and its partitioning into overstory/understory sources (Scott, Goodrich, and Levick 2003, 222-227).

Data Required: Remote sensing plus either ground Evapotranspiration (ET) data or remotely sensed land surface temp (Glenn et al. 2007, 139-168)

Quality of Output/Strengths: Accuracy depends on site-specific factors; sap flow techniques produce highly reliable data, if calibrated properly (Williams and Scott 2009); long term measurements increase quality, as do linkages to climate and water availability (Stromberg et al. 2009a)

Figure 9. Evapotranspiration Rates



Limitations/Weaknesses: Heterogeneity in vegetation means flux measurements may not be represented; other factors result in error bound of 20-30%; Bowen ratio method values cannot be checked for accuracy (Glenn et al. 2007, 139-168); assumptions (in Bowen method) about energy balance introduce error (Glenn et al. 2007, 139-168; Williams and Scott 2009, 37-56)

Use of Findings in Other Systems: Empirical vegetation index models cannot be used outside range of conditions were developed until proven locally (Glenn et al. 2007, 139-168; Williams and Scott 2009, 37-56).

c. WATER SOURCE STUDIES

Water source studies determine reliance of plants and animals on groundwater, surface water, or rain water, using either spatial contrasts or isotopes.

Spatial contrast water source studies:

Data Required: Streamflow/groundwater availability, data on rain events, amount of water used by plants and animals, ANOVA or MANOVA modeling systems (Stromberg et al. 2009a)

Quality of Output/Strengths: Long term measurements increase quality, as do linkages to climate and water availability (Stromberg et al. 2009a); dependent on an accurate assessment of water availability and consumption by the population studied (Snyder and Williams 2000, 227-240)

Limitations/Weaknesses: Fraction of water derived from groundwater varies between vegetation types, years, and in response to measurement error (Stromberg et al. 2009a)

Use of Findings in Other Systems: Unknown

Isotope water source studies:

Data Required: Isotope levels from water in plant, soil, etc., depth to groundwater or stream water, rainfall event information, ANOVA or MANOVA modeling systems (Snyder and Williams 2000, 227-240)

Quality of Output/Strengths: Long term measurements increase quality, as do linkages to climate and water availability (Stromberg et al. 2009b); dependent on an accurate assessment of water sample's isotope levels and source of water (Snyder and Williams 2000, 227-240)

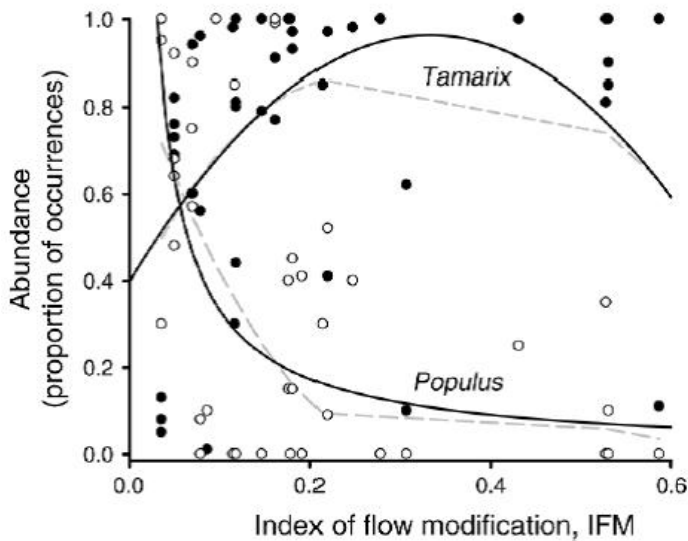
Limitations/Weaknesses: Unknown

Use of Findings in Other Systems: Unknown

d. ECO-FLOW RESPONSE CURVES

Eco-flow response curves depict quantitative relationships between surface flow or groundwater variables (i.e. a single hydrological element) and biological processes or states (Annear et al. 2004). The **biological processes** studied can include physiological processes (e.g., tree growth vs. stream flow rate); species-level processes (e.g., tree abundance/survivorship vs. groundwater decline rate); community-level conditions (e.g., abundance of wetland vegetation types or of obligate riparian birds vs. stream flow permanence); or ecosystem-level processes (e.g., flood frequency and primary productivity). Figure 10 relates riparian tree species abundance to an index of flow modification, demonstrating the utility of hydrological event models in correlative analyses (Merritt et al. 2010; Poff and Zimmerman 2010).

Figure 10. Eco-Flow Response Curve for Riparian Tree Species



Data Required: Several years of data on biological variables, flow attributes

Quality of Output/ Strengths: Choice of vegetation metric can be linked with sensitivity to short vs. long term hydrologic alteration (Merritt et al. 2010); riparian response guilds are more applicable than species-focused studies for prediction (Merritt et al. 2010)

Limitations/Weaknesses: Does not capture all sources of variability affecting biological response/species distribution, thus increasing the uncertainty of predictions (Annear et al. 2004; Merritt et al. 2010)

Use of Findings in Other Systems: Need to be applied to locations similar to those used to develop model (Annear et al. 2004); limited transferability even in the same hydroclimatic region because they are so river-specific, unless they are based on riparian response guilds calibrated to a region, in which case they apply to streams in similar stream classes (Merritt et al. 2010)

e. BIOLOGICAL EVENT MODELS

Biological event models characterize flow pulses designed to mobilize sediments, provide cues that initiate biological events (e.g. fish migration, spawning, flowering and seed set) and drive ecological processes. These include the Ecosystem Functions Model (HEC-EFM) and other biological event models.

The **Ecosystem Functions Model (HEC-EFM)** is designed to help determine ecosystem responses to changes in the flow regime of a river or connected wetland through statistical analyses of relationships between hydrology and ecology, hydraulic modeling, and use of Geographic Information Systems (GIS) to display spatial data (U.S. Army Corps, 2010).

Data Required: Time-series of daily mean flow and stage and parameters for variables to compute statistics relevant to an ecological response (Shafroth et al. 2010, 68-85); hydraulic modeling, and geographic information systems for the site (Hautzinger, Hickey, and Walker 2008, 28-30)

Quality of Output/Strengths: If applied to *Populus* spp., recruitment box model of high quality, if used for another species, lower quality (Merritt et al. 2010); produces spatially explicit predictions (Shafroth et al. 2010, 68-85)

Limitations/Weaknesses: Focus on *Populus* spp. for recruitment box; model assumes coupling of river stage and groundwater decline, which may not hold along gaining river reaches, in fine-textured substrates and at sites with complex substrate stratigraphy (Merritt et al. 2010)

Use of Findings in Other Systems: Model should be applicable to other river systems; provides hypotheses of ecological flow responses to be tested with additional studies (Shafroth et al. 2010, 68-85)

Other biological event models depict flows needed for recruitment events, such as the graphical model used by Mahoney and Rood (1998) to prescribe environmental flows for tree recruitment.

Data Required: Statistical analyses, hydraulic modeling, and geographic information systems for the site (Hautzinger, Hickey, and Walker 2008, 28-30)

Quality of Outputs/Strengths: Unknown

Limitations/Weaknesses: Unknown

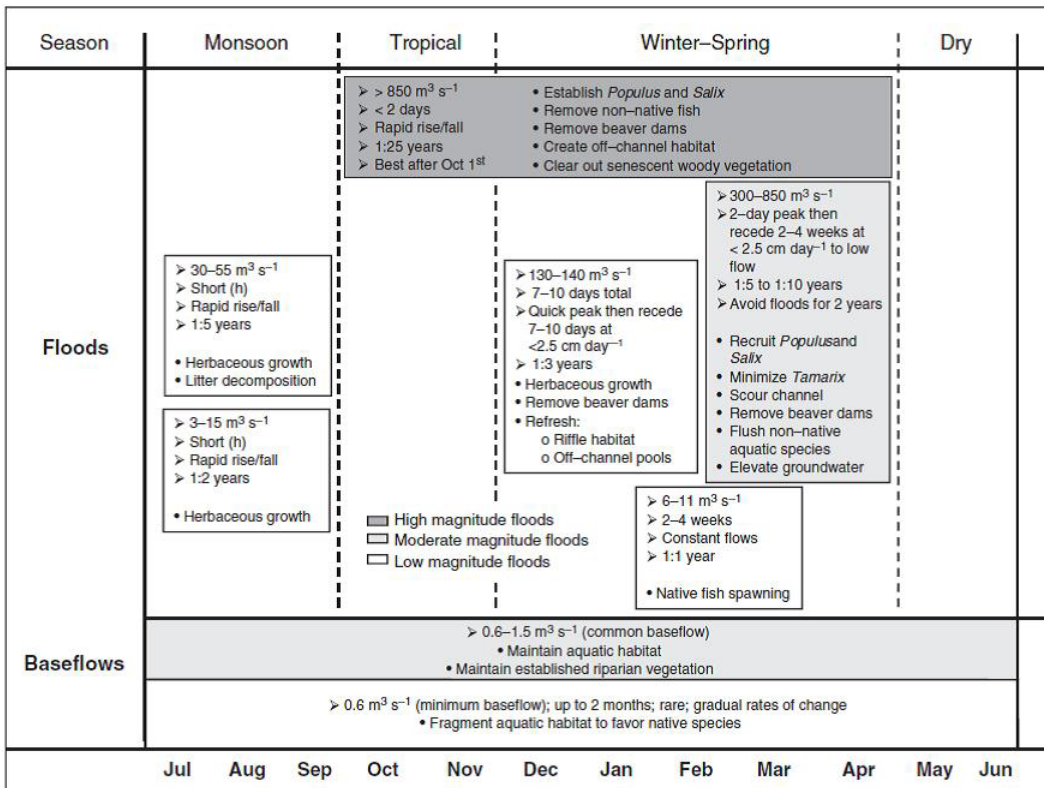
Use of Findings in Other Systems: Versatile: may be used to “predict biological outcomes of different river flows and stages” (Hautzinger, Hickey, and Walker 2008, 28-30)

C. HOLISTIC METHODS

In terms of **holistic, quantitative** methods, the following methods have been used in Arizona or are commonly referred to in the methods literature:

Holistic methods identify critical flow events for many or all major biological and physical components of the river system (Tharme 2003, 397-441; Katz 2006, 29-49). This includes the Building Block Methodology, other holistic methods,

Figure 11. Building Block Method Flow Regime Prescription



and the Ecological Limits of Hydrologic Alteration (ELOHA) framework. The last method in this class is not known to be applied in Arizona (i.e. used in any of the inventoried studies), but is commonly cited in the literature.

The Building Block Methodology uses a team of experts to identify basic elements of a flow regime on which important species rely (Dyson, Bergkamp, and Scanlon 2003, 118 pp.). Figure 11 presents the result of a BBM process defining flow requirements (Shafroth and Beauchamp 2006, 31; Shafroth et al. 2010, 68-85). Blocks include different flood flow and baseflow regimes within four seasons.

Data Required: Models of river hydraulics, groundwater-surface water dynamics, data on biotic responses and reservoir operations simulation (Shafroth et al. 2010, 68-85)

Quality of Outputs/Strengths: All aspects of hydrologic regime and ecosystem are studied (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); if biotic components used in model truly reflect needs of whole system, should encompass processes and conditions necessary to sustain biota (Stromberg et al. 2009a).

Limitations/Weaknesses: Expert opinion may be biased (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); constructing flow regime needs based on detailing key biological elements may omit critical flow characteristics (Tharme 2003, 397-441)

Use of Findings in Other Systems: Unknown

Other holistic methods identify critical flow events for many or all major biological and physical components of the river system.

Data Required: Team of experts (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); uses mix of available and newly acquired data in physical, biological, social science (Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Katz 2006, 29-49)

Quality of Outputs/Strengths: Flexible, robust (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); quality depends on resolution of data inputs (Poff et al. 2010)

Limitations/Weaknesses: Expert opinion may be biased (Dyson, Bergkamp, and Scanlon 2003, 118 pp.)

Use of Findings in Other Systems- Unknown

The **Ecological Limits of Hydrologic Alteration (ELOHA)** framework assesses e-flow needs across many streams at the regional scale, involving relationships between flow alteration and ecological responses. Uses available scientific knowledge and baseline and current hydrographs for stream segments to classify flow regime types, analyze flow alteration, and determine flow-ecological response relationships (as well as the certainty inherent in these; Arthington and Pusey 2003, Poff et al. 2010). This method has not been used in Arizona.

Data Required: Paired streamflow and ecological data from a region (Poff et al. 2010); able to utilize data of varying resolution (Poff et al. 2010); IHA (Poff et al. 2010); economic, sociological, hydrologic, geomorphologic, water quality, ecological, and agricultural inputs (Conserve Online 2010)

Quality of Outputs/Strengths: Quality depends on resolution of data inputs (Poff et al. 2010)

Limitations/Weaknesses: Will involve scientific uncertainty because of other determinants than hydrologic alteration that aren't considered (Poff et al. 2010)

Use of Findings in Other Systems: ELOHA relationships should be relevant to streams of similar hydrologic and geomorphologic classification (Poff et al. 2010)

D. QUALITATIVE METHODS

In terms of **qualitative** methods, the following methods have been used in Arizona or are commonly referred to in the methods literature:

Descriptions of the **distribution of flora and fauna associated with water sources** (springs, riparian areas, etc.).

Flow-ecology response curves. Figure 12 is an example of a non-quantitative flow-ecology response curve that focuses on the response of fish species richness and biomass to changes in baseflow (Haney et al. 2008, 114).

Descriptions of **flow-ecology response relationships.**

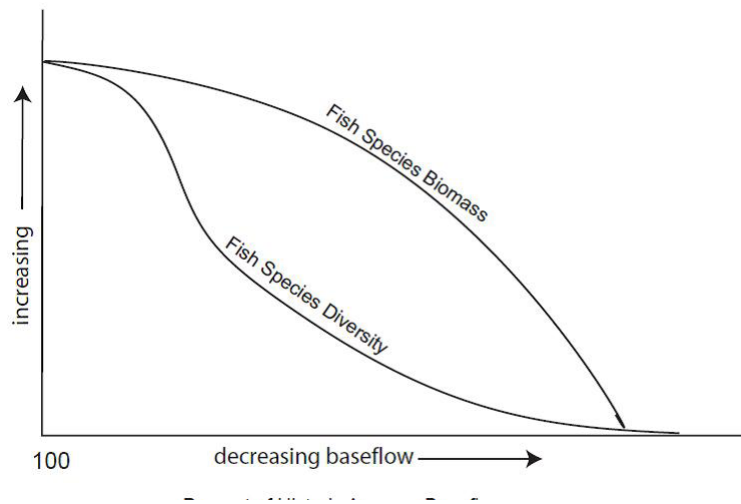
Data Required: Unknown

Quality of Outputs/Strengths: Unknown

Limitations/Weaknesses: Unknown

Use of Findings in Other Systems: Unknown

Figure 12. Qualitative Flow-Ecology Response Curve for Fish



[STUDY REFERENCES](#)

Each methods class from the inventory of studies has a set of studies associated with it. Refer to Appendix B for a list of studies by methods class. Authors of these papers have experience applying these methods.

DISCUSSION

Around the world, holistic methods are the most commonly used approach for quantifying environmental water needs (Tharme 2003, 397-441; Richter et al. 2006, 297-318). However, in the United States, the holistic methods are not as widely used (Tharme 2003, 397-441). From our assessment, holistic methods have been the type of method least used in Arizona's environmental flows studies.

The use of several methods in conjunction in a single study, as well as adaptations of existing methodologies to tailor them to local needs, suggests that in Arizona, the science of determining environmental water needs is increasingly sophisticated. One particular example of this is the limited use of hydrologic index methods and the use of hydraulic methods in combination with other methods, never by themselves. This last point may be an artifact of the inventory's focus on ecological water needs and not (directly) on the flows needed to maintain abiotic processes within rivers and riparian ecosystems.

The extensive reliance on correlative methods may be problematic for transferability of data across systems, as well as for providing robust predictions of flow responses. On the other hand, where correlative studies address multiple flow components and multiple species, they are a significant improvement on hydrology-based e-flows methods. As long as their findings are interpreted appropriately (see Merritt et al. 2010 and Dyson et al. 2003), they can provide important insights into the relationships between water and environmental attributes.



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

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APPENDICES

- A. Glossary
- B. List of Studies by Method
- C. Additional and Anticipated studies
- D. Methods Evaluation Table

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

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

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 METHOD

1. Riparian Methods

a. Hydrological Event Models: IHA/RVA

- i. Briggs. 2008. "Water Requirements for Bottomland vegetation of middle Rincon Creek and potential threats to water availability"
- ii. Briggs, M.K.; Magirl, C.; Hess, S. 2007. "Hydrologic function and channel morphologic analysis of the Santa Cruz River at the North Simpson Site"
- iii. Merritt, D.M.; Poff, N.L. 2010. "Shifting dominance of riparian Populus and Tamarix along gradients of flow alteration in western North American rivers"

b. Water Budget/Evapotranspiration Studies

- i. ADWR. 2005. "Groundwater use estimates for riparian inventory of the Benson sub-area - Appendix E"
- ii. Gazal, R.M.; Scott, R.L.; Goodrich, D.C.; Williams, D.G. 2006. "Controls on transpiration in a semiarid riparian cottonwood forest."
- iii. 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 evapotranspiration using remote and in site measurements."
- iv. 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."
- v. Leenhouts, J. M., Stromberg, J. C., and Scott, R. L.. 2006. "Hydrologic Requirements of and Consumptive Ground-water Use by Riparian Vegetation along the San Pedro River, Arizona"
- vi. Pima County. 2009. "City of Tucson and Pima County Riparian Protection Technical Paper"
- vii. Pima County. 2009. "City of Tucson and Pima County Water for the Environment Technical Paper"
- viii. Pima County. 2000. "Preliminary Riparian Protection, Management, and Restoration Element"
- ix. 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."
- x. 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."
- xi. Scott, R.L.; Goodrich, D.C.; Levick, L.R. 2003. "A GIS-based management tool to quantify riparian vegetation groundwater use"
- xii. 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"
- xiii. Shafroth, P., , Wilcox, A., Lytle, D., Hickey, John T., Andersen, D., Beauchamp, V., Hautzinger, A., McMullen, L., Warner, A. 2010. "Ecosystem effects of environmental flows: modeling and experimental floods in a dryland river"
- xiv. Springer, A. E., Wright, J. M., Shafroth, P. B., Stromberg, J. C., Patten, D. T.. 1999. "Coupling ground water and riparian vegetation models to assess effects of reservoir releases"

- xv. Stromberg. 2001. "Influence of stream flow regime and temperature on growth rate of the riparian tree, *Platanus wrightii*, in Arizona"
- xvi. Stromberg. 2008. "Verde River Ecological Flows Study - Background: Stream Flow Regimes and Riparian Vegetation of the Verde River (Chapter 4)"
- xvii. 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)"

c. Water Source Studies: Spatial contrasts

- i. 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"

d. Water Source Studies: Use of Isotopes

- i. 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.; Marssett, R.; Ni, W. 2000. "Seasonal estimates of evapotranspiration using remote and in site measurements."
- ii. 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)"

e. Eco-Flow Response Curves-Physiological Processes

- i. Busch; Smith. 1995. "Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern U.S."
- ii. Horton, J.L.; Kolb, T.E.; Hart, S.C. 2001. "Physiological response to groundwater depth varies among species and with river flow regulation"
- iii. 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."
- iv. 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."
- v. Stromberg, J.C. 2001. "Biotic integrity of *Platanus wrightii* riparian forests in Arizona: first approximation"
- vi. Stromberg, J.C. 2001. "Influence of stream flow regime and temperature on growth rate of the riparian tree, *Platanus wrightii*, in Arizona"
- vii. Tallent-Halsell, N.G.; Walker, L.R. 2002. "Responses of *Salix gooddingii* and *Tamarix ramosissima* to flooding"

f. Eco-Flow Response Curves-Species-Level Processes

- i. 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."
- ii. Busch; Smith. 1995. "Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern U.S."
- iii. 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)"
- iv. Horton, J.L.; Kolb, T.E.; Hart, S.C. 2001. "Physiological response to groundwater depth varies among species and with river flow regulation"

- v. 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"
- vi. Kearsley, M.J.C.; Ayers, T.J. 2009. "Riparian vegetation responses: snatching defeat from the jaws of victory and vice versa."
- vii. 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)"
- viii. 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."
- ix. Kirkpatrick, C.; Conway, C.J.; LaRoche, D. 2009. "Surface water depletion and riparian birds"
- x. 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"
- xi. Leenhouts, J. M., Stromberg, J. C., and Scott, R. L.. 2006. "Hydrologic Requirements of and Consumptive Ground-water Use by Riparian Vegetation along the San Pedro River, Arizona"
- xii. Lite, Stromberg. 2005. "Surface water and ground-water thresholds for maintaining Populus-Salix forests, San Pedro River, Arizona"
- xiii. Melis, T. S., David J. Topping, Paul E. Grams, David M. Rubin, Scott A Wright, Amy E. Draut, Joseph E. Hazel, Jr., Barbara E. Ralston, Theodore A. Kennedy, Emma Rosi-Marshall, Josh Korman, Kara D. Hilwig, and Lara M. Schmit. (USGS). 2010. "2008 High-flow experiment at Glen Canyon Dam benefits Colorado River Resources in Grand Canyon National Park"
- xiv. Merritt, D.M.; Poff, N.L. 2010. "Shifting dominance of riparian Populus and Tamarix along gradients of flow alteration in western North American rivers"
- xv. National Park Service. 2008. "Assessment Report Water-Right Application No. 33-96733 For In stream-Flow Maintenance. Middle Reach of Rincon Creek, Pima County, Arizona"
- xvi. 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."
- xvii. 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."
- xviii. Shafroth, P, Wilcox, A., Lytle, D., Hickey, John T., Andersen, D., Beauchamp, V., Hautzinger, A., Mc Mullen, L., Warner, A. 2010. "Ecosystem effects of environmental flows: modeling and experimental floods in a dryland river"
- xix. 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."
- xx. Shafroth, P.B.; Beauchamp. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Streamflow-Biota Relations: Riparian Vegetation (Chapter 3)"
- xxi. Stromberg, J.C. 2001. "Biotic integrity of Platanus wrightii riparian forests in Arizona: first approximation"
- xxii. Stromberg, J.C. 2001. "Influence of stream flow regime and temperature on growth rate of the riparian tree, Platanus wrightii, in Arizona" Stromberg et al. 2005. "Effects of stream flow intermittency on riparian vegetation of a semiarid region river (San Pedro River, Arizona)"
- xxiii. Stromberg, J.C. 1993. "Instream flow models for mixed deciduous riparian vegetation within a semiarid region"

- xxiv. Stromberg, J.C. 2008. "Verde River Ecological Flows Study - Background: Stream Flow Regimes and Riparian Vegetation of the Verde River (Chapter 4)"
- xxv. 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"
- xxvi. Stromberg, J.C.; Tiller, R.; Richter, B. 1996. "Effects of groundwater decline on riparian vegetation of semiarid regions: The San Pedro, Arizona"
- xxvii. Tallent-Halsell, N.G.; Walker, L.R. 2002. "Responses of *Salix gooddingii* and *Tamarix ramosissima* to flooding"
- xxviii. van Riper; Paradzick. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Streamflow-Biota Relations: Birds (Chapter 4)"

g. Eco-Flow Response Curves-Community Level Conditions

- i. 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"
- ii. 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 groundwater and riparian floodplain vegetation along a dryland river: a scenario analysis"
- iii. Katz, G.L.; Stromberg, J.C.; Denslow, M.C. 2009. "Streamside herbaceous vegetation response to hydrologic restoration on the San Pedro River, Arizona"
- iv. Kearsley, M.J.C.; Ayers, T.J. 2009. "Riparian vegetation responses: snatching defeat from the jaws of victory and vice versa."
- v. 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)"
- vi. 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."
- vii. Kirkpatrick, C.; Conway, C.J.; LaRoche, D. 2009. "Surface water depletion and riparian birds"
- viii. Leenhouts, J. M., Stromberg, J. C., and Scott, R. L. 2006. "Hydrologic Requirements of and Consumptive Ground-water Use by Riparian Vegetation along the San Pedro River, Arizona"
- ix. Lite; Stromberg. 2005. "Surface water and ground-water thresholds for maintaining *Populus-Salix* forests, San Pedro River, Arizona"
- x. National Park Service. 2008. "Assessment Report Water-Right Application No. 33-96733 For Instream-Flow Maintainance. Middle Reach of Rincon Creek, Pima County, Arizona"
- xi. 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."
- xii. Scalero, D. 2009. "Final report: Pantano Jungle restoration Cienega Creek Natural Preserve"
- xiii. Stromberg, J.C. 2001. "Biotic integrity of *Platanus wrightii* riparian forests in Arizona: first approximation"
- xiv. Stromberg, J.C. 1993. "Instream flow models for mixed deciduous riparian vegetation within a semi arid region"
- xv. Stromberg, J.C.; Bagstad, K.J.; Leenhouts, J.M.; Lite, S.J.; Makings, E.. 2005. "Effects of stream flow intermittency on riparian vegetation of a semiarid region river (San Pedro River, Arizona)"

- xvi. 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)"
- xvii. Stromberg, J.C.; Lite, S.J.; Beauchamp, V. 2003. "Managing stream flow regimes for riparian ecosystem restoration"
- xviii. 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"
- xix. Stromberg, J.C.; Tiller, R.; Richter, B. 1996. "Effects of groundwater decline on riparian vegetation of semiarid regions: The San Pedro, Arizona"
- xx. Villarreal, M.L. 2009. "Land use and disturbance interactions in dynamic arid systems: Multiscale remote sensing approaches for monitoring and analyzing riparian vegetation change."

h. Biological Event Models: HEC-EFM

- i. Shafroth, P, Wilcox, A., Lytle, D., Hickey, John T., Andersen, D., Beauchamp, V., Hautzinger, A., McMullen, L., Warner, A. 2010. "Ecosystem effects of environmental flows: modeling and experimental floods in a dryland river"

i. Biological Event Models: Other

- i. 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."
- ii. 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."
- iii. Shafroth, P.B.; Beauchamp. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Streamflow-Biota Relations: Riparian Vegetation (Chapter 3)"
- iv. Springer, A. E., Wright, J. M., Shafroth, P. B., Stromberg, J. C., Patten, D. T. 1999. "Coupling groundwater and riparian vegetation models to assess effects of reservoir releases"

2. Aquatic Methods

a. Hydrologic: Great Plains method

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

b. Hydrologic description of e-flow relationships: Narrative Justification

- i. Briggs. 2008. "Water Requirements for Bottomland vegetation of middle Rincon Creek and potential threats to water availability"
- ii. National Park Service. 2008. "Assessment Report Water-Right Application No. 33-96733 For Instream-Flow Maintenance. Middle Reach of Rincon Creek, Pima County, Arizona"

c. Hydraulic rating: 1-d HEC-RAS

- i. Briggs. 2008. "Water Requirements for Bottomland vegetation of middle Rincon Creek and potential threats to water availability"
- ii. Briggs, M.K.; Magirl, C.; Hess, S. 2007. "Hydrologic function and channel morphologic analysis of the Santa Cruz River at the North Simpson Site"
- iii. Leenhouts, J. M., Stromberg, J. C., and Scott, R. L., 2006. "Hydrologic Requirements of and Consumptive Ground-water Use by Riparian Vegetation along the San Pedro River, Arizona"

- viii. National Park Service. 2008. "Assessment Report Water-Right Application No. 33-96733 For Instream-Flow Maintenance. Middle Reach of Rincon Creek, Pima County, Arizona"
- ix. Pima County. 2009. "City of Tucson and Pima County Riparian Protection Technical Paper"
- x. Pima County. 2000. "Preliminary Riparian Protection, Management, and Restoration Element"
- xi. Rosen, P.C. 2009. "Ecology and Conservation of the San Pedro River - Reptiles and Amphibians (Chapter 9)"
- xii. Schmidt, J.C.; Webb, R.H.; Valdez, R.A.; Marzolf, G.R. 1998. "Science and values in river restoration in the Grand Canyon"
- xiii. 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)"
- xiv. Springer, A. E., Wright, J. M., Shafroth, P. B., Stromberg, J. C., Patten, D. T. 1999. "Coupling groundwater and riparian vegetation models to assess effects of reservoir releases"
- xv. 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)"
- xvi. U.S. Fish and Wildlife Service. 2008. "Final Biological Opinion for the Operation of the Glen Canyon Dam"

b. Description of e-flow relationships: Flow ecology curve

- i. Turner; Haney. 2008. "Verde River Ecological Flows Study - Workshop Results: Steps Toward Understanding Ecological Response to Hydrologic Variation in the Verde River (Chapter 6)"

c. Description of e-flow relationships: Flow ecology relationships

- i. Andersen. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Ecosystem Functioning (Chapter 7)"
- ii. Andersen. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Stream flow-Biota Relations: Mammals, Reptiles, Amphibians, and Floodplain Invertebrates (Chapter 6)"
- iii. 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"
- iv. Bodner, G.; Simms, J.; Gori, D. 2007. "State of the Las Cienegas National Conservation Area: Gila topminnow population status and trends 1989-2005"
- v. 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)"
- vi. Briggs. 2008. "Water Requirements for Bottomland vegetation of middle Rincon Creek and potential threats to water availability"
- vii. Briggs, M.K.; Magirl, C.; Hess, S. 2007. "Hydrologic function and channel morphologic analysis of the Santa Cruz"
- xxv. 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)"
- xxvi. Springer, A. E., Wright, J. M., Shafroth, P. B., Stromberg, J. C., Patten, D. T. 1999. "Coupling groundwater and riparian vegetation models to assess effects of reservoir releases"
- xxvii. 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)"

- xxviii. Stevens, L. E., Turner, D. S., and Supplee, V. 2008. "Verde River Ecological Flows Study - Background: Wildlife and Flow Relationships in the Verde River Watershed (Chapter 5)"
- xxix. Stromberg. 2008. "Verde River Ecological Flows Study - Background: Stream Flow Regimes and Riparian Vegetation of the Verde River (Chapter 4)"
- xxx. Turner; Haney. 2008. "Verde River Ecological Flows Study - Workshop Results: Steps Toward Understanding Ecological Response to Hydrologic Variation in the Verde River (Chapter 6)"
- xxxi. U.S. Fish and Wildlife Service. 2008. "Final Biological Opinion for the Operation of the Glen Canyon Dam"
- xxxii. Valdez, R.A; Shannon, J.P.; Blinn, D.W. 1999. "Biological implications of the 1996 Controlled Flood"
- xxxiii. van Riper; Paradzick. 2006. "Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona - Streamflow-Biota Relations: Birds (Chapter 4)"

5. Valuation Methods

a. Real Estate Indices/Hedonic Valuation

- i. Bark, R.H.; Osgood, D.E.; Colby, B.G.; Katz, G.; Stromberg, J. 2009. "Tucson Study of Human Preferences for Riparian Habitat"
- ii. 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)"
- iii. Bourne, K.L. 2007. "The effect of the Santa Cruz River riparian corridor on single family home prices using the hedonic pricing method"
- iv. Colby, B.G.; Wishart, S. 2002. "Riparian areas generate property value premium for landowners"

b. Direct Use Values/Market Pricing

- i. Marcus. 2009. "Glen Canyon Dam Releases - Economic Considerations"

c. Expenditures Indices

- i. Bureau of Reclamation. 2008. "Final environmental assessment experimental releases from Glen Canyon Dam, Arizona 2008-2012"
- ii. Leenhouts, J. M., Stromberg, J. C., and Scott, R. L., 2006. "Hydrologic Requirements of and Consumptive Ground-water Use by Riparian Vegetation along the San Pedro River, Arizona"
- iii. Orr, P.; B. Colby. 2002. "Expenditures by nature-oriented visitors and their economic implications in the Upper San Pedro River Valley"
- iv. Pima County. 2009. "City of Tucson and Pima County Water for the Environment Technical Paper"

d. Activity/Participation/Visitation Numbers

- i. Bureau of Reclamation. 2008. "Final environmental assessment experimental releases from Glen Canyon Dam, Arizona 2008-2012"
- ii. Leenhouts, J. M., Stromberg, J. C., and Scott, R. L. 2006. "Hydrologic Requirements of and Consumptive Ground-water Use by Riparian Vegetation along the San Pedro River, Arizona"
- iii. Orr, P.; B. Colby. 2002. "Expenditures by nature-oriented visitors and their economic implications in the Upper San Pedro River Valley"

iv. Pima County. 2009. "City of Tucson and Pima County Water for the Environment Technical Paper"

e. Values Survey

i. West, P.; Smith, D.H.; Auberle, W. 2009. "Valuing the Verde River watershed: an assessment"

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, David L., Gido, Keith B., Stefferud, Jerome A.. 2008. "Natural Flow Regimes, Nonnative Fishes, and Native Fish Persistence in Arid Land River Systems"
- iii) Stromberg, J. C., Beauchamp, V. B., Dixon, M. D., Lite, S. J., Paradzick, C.2007. "Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid southwestern 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, M., Hyun, K., Tognetti, S. 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, L. Arriana, White, Gary C, Noon, Barry R.. 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, Arun K., Hogan, James F., Ekwurzel, Brenda, Baillie, Matthew N., Eastoe, Christopher J. 2007. "Geochemical quantification of semiarid mountain recharge "

6) Santa Cruz

a) Riparian

- i) Unland, Helene E., Arain, Altaf M., Harlow, Chawn, Houser, Paul R., Garatuza-Payan, Jaime, Scott, Paul Sen, Omer L., Shuttleworth, W. James 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. (RM)

c) Little Colorado River

- i.) ADEQ stream assessment

d) Lower Colorado River

- i) Paretto, N. LCR EMAP

e) 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. (RM)

f) Verde River

- i) Springer lab. "Verde Valley Surface Water Modeling project" (fall 2010)

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 – ask Grant Loomis in Phoenix FS office for more info (RB)

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. van Leeuwen, and J.R. Leon-Romo. 2010. "Mapping and monitoring riparian vegetation distribution, structure and composition with regression tree models and post-classification change metrics." Ecological Indicators. 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) Analysis of valuation surveys by Brookshire et al. (upcoming)

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."

APPENDIX D. METHODS EVALUATION TABLE

Key: **Brown cell = information included in decision trees** **Gray cell = no data available in literature reviewed** *** = depends on information available**

<i>Hydrological Context</i>	<i>Method Class</i>	<i>Specific Method</i>	<i>Use/Purpose in decision making</i>	<i>Use/Purpose in decision making CATEGORIES</i>	<i>Use/Purpose in science process</i>	<i>Quantitative or Qualitative?</i>	<i>Cost/Effort/Time/Expertise required</i>	<i>Cost/Effort/Time/Expertise required CATEGORIES</i>	<i>Scale</i>
AQUATIC	Hydrological Index	Great Plains Method	Planning level of water resource development or as preliminary flow targets (Tharme 2003) ; appropriate in low controversy settings (ADWR 1991, Tharme 2003).	Setting flows needed for conservation or restoration goals - Maintain natural flow regime; Measuring progress towards conservation or restoration goals - Maintaining natural flow regime.		Quantitative	Rapid, non-resource intensive (Tharme 2003). Office based, Low to moderate data and cost requirements (EFM website)	LOW TO MODERATE	It has been applied on all sizes of stream in the USA.
AQUATIC		Narrative Justification, using monthly mean flows	Part of the Instream Flow Water Right Application "Documents the relationship between the beneficial uses and instream flow" which can be used to identify and describe the uses for the instream flow rights being "sought" (ADWR 1991).	Setting flows needed for conservation or restoration goals - Beneficial use.	"Documents the relationship between the beneficial uses and instream flow" which may result in identifying and studying a "unique habitat...or species dependent on the flow" (ADWR 1991).	Quantitative	Low, minimal, only for info gathering, moderate (expertise needed to describe beneficial uses/physical setting) (ADWR 1991).	LOW TO MODERATE	River/stream reaches (ADWR 1991).
AQUATIC	Hydraulic Rating	1-d hydraulic models – HEC-RAS	Establishing stage-discharge relation in unsteady flow situations (Annear 2004); recommends flows necessary for channel and floodplain maintenance (Annear 2004).	Setting flows needed for conservation or restoration goals - Maintaining channel and floodplain; Measuring progress towards conservation or restoration goals - Maintaining channel and floodplain.	May be used with MODFLOW, HEC-RAS, or HEC-ResSim when "connected with...the Ecosystem Functions Model (HEC-EFM) to predict biological outcomes of different river flows and stages" (Hautzinger et al 2008); Describing system dynamics. Average flow velocity.	Quantitative	Moderate to high expertise (ADWR 1991, Annear 2004).	MODERATE TO HIGH	River (Shafroth et al 2010)
AQUATIC		2-d hydraulic models	Minimal (Annear 2004).	Setting flows needed for conservation or restoration goals - Maintaining channel and floodplain; Measuring progress towards conservation or restoration goals - Maintaining channel and floodplain	2-d hydraulic models can be linked with hydraulic habitat models to create habitat-dicharge simulations (Annear 2004).	Quantitative	2-d hydraulic models require moderate to high cost, effort and intensive site-specific analyses (ADWR 1991, Annear 2004).	MODERATE TO HIGH	River reaches and segments (Annear 2004).

Hydrological Context	Method Class	Specific Method	Use/Purpose in decision making	Use/Purpose in decision making CATEGORIES	Use/Purpose in science process	Quantitative or Qualitative?	Cost/Effort/Time/Expertise required	Cost/Effort/Time/Expertise required CATEGORIES	Scale
AQUATIC		Hydraulic rating-Other (e.g. HEC-5)		Setting flows needed for conservation or restoration goals - Maintaining channel and floodplain.	Can be used as tools within holistic methodologies (Tharme 2003), such as inputs of habitat information for the ELOHA framework (Poff et al 2010).	Quantitative	Cheap and simple to calculate (Annear 2004, Katz 2006); adding ecological data adds time needed to collect (Dyson 2003).	LOW TO MODERATE	Reach (Annear 2004)
AQUATIC	Habitat Simulation	Instream Flow Incremental Methodology (IFIM)	Comparisons between baseline and other scenarios/tradeoffs analysis in decision making (Dyson 2003); evaluating alternative flow regulation scenarios (Tharme 2003); instream flow prescriptions for species (Annear 2004); mitigation plan development (Annear 2004).	Setting flows needed for conservation or restoration goals - Maintaining hydraulic habitat; Management impact analysis/scenario planning->mitigation plan development; Quantifies habitat available under alternative flow regimes.	Habitat duration curves could be developed to consider periods of habitat persistence related to key biological time-windows (Petts 2009). Habitat assessment methods can be used as part of ELOHA (Poff et al 2010).	Quantitative	Involves engagement/negotiation with stakeholders (Dyson 2003, Annear 2004); clear manuals available (Tharme 2003); low-moderate cost, effort, and time if data/program available, moderate expertise needed to understand fish/habitat relationship, data, software (ADWR 1991).	LOW TO MODERATE*	River segments, stream networks, and subbasins; PHABISM Results are based on microhabitat and are applied within mesohabitats to describe river reaches (Annear 2004).
AQUATIC		Habitat Simulation - Other		Setting flows needed for conservation or restoration goals - Maintaining hydraulic habitat; Management impact analysis/scenario planning->mitigation plan development; Quantifies habitat available under alternative flow regimes.	Habitat duration curves could be developed to consider periods of habitat persistence related to key biological time-windows (Petts 2009). Habitat assessment methods can be used as part of ELOHA (Poff et al 2010).	Quantitative	Takes long time, requires skilled expertise, can be expensive (Dyson 2003, Katz 2006, Petts 2009); clear manuals available (Dyson 2003).	MODERATE TO HIGH	River segment to reach (Annear 2004).
AQUATIC	Biological Response to Flow Correlation	Correlation of flow attributes with biological characteristics .	Predict biological response to flows/analyze management scenarios in stream and stream types where developed (Annear 2004); flow recommendation when considered in conjunction with management objectives (Annear 2004); initial impact assessment for large area (Dyson 2003); provides trend information useful for identifying thresholds (Annear 2004).	Setting flows needed for conservation or restoration goals - Other ecological objectives; Management impact analysis/scenario planning->mitigation plan development - Predict biological response to flow scenarios.	Provides hypotheses of ecological flow responses to be tested with additional studies (Annear 2004).	Quantitative	Moderate to very high; involves field data collection (Annear 2004).	MODERATE TO HIGH	Reach, subwatershed, watershed, region (Annear 2004).
AQUATIC		Correlation of water quality with biological characteristics							

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RIPARIAN	Hydrological event models	IHA/RVA method	To compare current conditions to a hydrological baseline (Richter undated); future alternatives analysis in support of planning instream flow studies (Richter undated, Tharme 2003); reveal direction and magnitude of hydro alterations (Richter undated).	Setting flows needed for conservation or restoration goals - Maintaining natural flow regime; Measuring progress towards conservation or restoration goals - Maintaining natural flow regime; Management impact analysis/scenario planning->mitigation plan development* (requires data on impacts of future climate or development scenarios).	Used in conjunction with metrics that more directly evaluate biological characteristics of an ecosystem (Richter undated); can be inputs to ELOHA for hydrologic classification (Poff et al 2010).	Quantitative	Easy to calculate with software given data is available; office technique (Annear 2004).	LOW TO MODERATE*	River reach or basin depending upon the breadth of application (Annear 2004).
RIPARIAN	Biological Event Models	Other	Flow needs for maintaining vegetation community structure.	Setting flows needed for conservation or restoration goals - Maintaining vegetation.	Can be used to determine flow characteristics needed to maintain riparian ecosystems; May be used to combine MODFLOW, HEC-RAS, and/or HEC-ResSim "to predict biological outcomes of different river flows and stages" (Hautzinger et al 2008).	Quantitative	Minimal cost, effort, and time assuming the data is available (Hautzinger et al 2008).	LOW TO MODERATE*	
RIPARIAN		HEC-EFM	Comparing predicted outcomes of flow scenarios "allows reservoir releases and alternative water management policies to be tested before implementation to see potential impacts to the habitats of T&E species" (Hautzinger et al 2008).	Management impact analysis/scenario planning->mitigation plan development.	Provides hypotheses of ecological flow responses to be tested with additional studies (Shafroth et al 2010).	Quantitative	Moderate expertise needed to create models with HEC-EFM software (Hautzinger et al 2008).	MODERATE TO HIGH	Rivers (Hautzinger et al 2008)and river reaches (Merritt et al 2010).
RIPARIAN	Water budget/ Evapotranspiration studies		Predict biological response to groundwater declines; define seasonal and annual vegetative needs for water (Glenn et al 2007); irrigation scheduling, watershed management, weather forecasting, and projecting the long-term effects of land use change (Glenn et al 2007).	Setting flows needed for conservation or restoration goals - Maintaining vegetation; Management impact analysis/scenario planning->mitigation plan development - Predict biological response to flow scenarios - groundwater declines.	ET rate can be used to show the groundwater or stress level of riparian plants (Williams and Scott, Ch.2); Needed to understand how riparian vegetation influences the groundwater hydrology of stream catchments (Williams and Scott 2009).	Quantitative	Bowen ratio method is simpler than the eddy covariance method, but both methods require \$10-30,000/tower and a team of scientists (Glenn et al 2007).	MODERATE TO HIGH	River reach (Williams and Scott, Ch. 2, pg 44).

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RIPARIAN	Water source studies	Spatial contrasts	To determine reliance of plants and animals on groundwater, surface water, or rain water which can support or influence water allocation, use, etc. (Snyder and Williams 2000).	Management impact analysis/scenario planning->mitigation plan development.	Needed to understand how riparian vegetation influences the groundwater hydrology of stream catchments (Williams and Scott 2009). Provides a foundation for predicting biological responses to changes in flow (Snyder and Williams 2000).	Quantitative	Moderate to high for all (dependant on size/depth of study) (interpreted from Snyder and Williams 2000).	MODERATE TO HIGH	River reach (Snyder and Williams 2000).
RIPARIAN		Use of isotopes	Hydrogen and oxygen isotope concentrations and the resulting transpiration levels indicates from which source(s) a plant obtains water and the “responses of [plant] species...[to] groundwater availability” (Snyder and Williams 2000).	Management impact analysis/scenario planning->mitigation plan development.	Needed to understand how riparian vegetation influences the groundwater hydrology of stream catchments (Williams and Scott 2009). May be combined with Linear Mixing Models to provide evidence of root system functions and show isotope ratios in plants and soil; shows “responses of [plant] species across sites with very different patterns of groundwater availability” (Snyder and Williams 2000).	Quantitative	Moderate to high cost, effort, time (dependant on size of study), high expertise (required for isotope measurements) (interpreted from Snyder and Williams 2000).	MODERATE TO HIGH	Large scale studies; River reach (Snyder and Williams 2000).
RIPARIAN	Eco-Flow response curves	Focus on physiological processes; species-level processes; community-level conditions; or ecosystem-level processes	Prediction of biological responses to flows/analyze management scenarios in stream where developed (Merritt et al 2010); set interim flow standards for testing and adaptive management (Petts 2009); flow recommendation in conjunction with management objectives in some cases (e.g. those using riparian response guilds); evaluate tradeoffs between flow alteration and riparian conditions (Merritt et al 2010).	Setting flows needed for conservation or restoration goals - General ecological objectives; Measuring progress towards conservation or restoration goals - General ecological objectives; Management impact analysis/scenario planning->mitigation plan development - Predict biological response (single or multiple species) to flow scenarios.	Provides hypotheses of ecological flow responses to be tested with additional studies.	Quantitative	Moderate to very high; involves field data collection (Annear 2004).	MODERATE TO HIGH	River reaches (Merritt et al 2010); tend to be river and site-specific (Merritt et al 2010).
HOLISTIC	Holistic methods	Building block methodology	Impact assessment or restoration planning by reach (Dyson 2003, Tharme 2003); comprehensive ecosystem protection (Katz 2006); when high social, environmental, or economic costs are at stake (Katz 2006).	Setting flows needed for conservation or restoration goals - General ecological objectives; Management impact analysis/scenario planning->mitigation plan development - Predict biological response (single or multiple species) to flow scenarios.		Quantitative	Manual available (Tharme 2003).	MODERATE TO HIGH	River, river reach (Dyson 2003, Tharme 2003).

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HOLISTIC		Holistic - Other		Setting flows needed for conservation or restoration goals - General ecological objectives; Management impact analysis/scenario planning->mitigation plan development - Predict biological response (single or multiple species) to flow scenarios.		Quantitative	Take a long time, require skilled expertise and specific method for process, can be VERY expensive (Dyson 2003, Katz 2006).	MODERATE TO HIGH	River, river reach (Dyson 2003, Tharme 2003).
AQUATIC/ RIPARIAN/ HOLISTIC	Non-quantitative Methods	Distribution of flora and fauna associated with water sources (springs, riparian areas, etc.).	Indication of species that may have been lost from past flow reductions or could be threatened by future flow reductions.	Management impact analysis/scenario planning->mitigation plan development - non-quantitative.	When coupled with ecological gradient information, can help to predict distribution under changing conditions (Merritt et al 2010).	Qualitative		LOW TO MODERATE	River reaches (Merritt et al 2010).
AQUATIC/ RIPARIAN/ HOLISTIC		Flow-ecology response curves/ELOHA	Provides hypotheses of ecological flow responses to be tested with additional studies.	Management impact analysis/scenario planning->mitigation plan development - non-quantitative.	Provides hypotheses of ecological flow responses to be tested with additional studies.	Qualitative		LOW TO MODERATE	
AQUATIC/ RIPARIAN/ HOLISTIC		Flow-ecology response relationship description	Provides hypotheses of ecological flow responses to be tested with additional studies.	Management impact analysis/scenario planning->mitigation plan development - non-quantitative.	Provides hypotheses of ecological flow responses to be tested with additional studies.	Qualitative		LOW TO MODERATE	

Key: **Brown cell = information included in decision trees** **Gray cell = no data available in literature reviewed** *** = depends on information available**

<i>Hydrological Context</i>	<i>Method Class</i>	<i>Specific Method</i>	<i>Data Required</i>	<i>Quality of Output/Strengths</i>	<i>Limitations/Weaknesses</i>	<i>Use of findings in other systems</i>
AQUATIC	Hydrological Index	Great Plains Method	Daily hydrographs from a period of record	Provides satisfactory preservation flows, for most fish species; can be used to analyze general habitat for fish, wildlife and recreation; developed largely for streams with highly seasonal flow patterns, and monthly flows are assessed to incorporate this variability (Tharme 2003, 397-441)	Best used when prior data exist and needs field testing in different regions of the USA; some elements of EFR are based on professional opinion; should only be applied to rivers with similar morphology as where developed; does not include most extreme year types (Tharme 2003, 397-441)	
AQUATIC		Narrative Justification, using monthly mean flows	Documentation of preexisting hydrologic records: monthly mean flows (Arizona Department of Water Resources 1991, 34)	"The primary use of this method is for...streams where there is little or no controversy or challenge and where no increase in consumptive use is anticipated. However, because the method will save considerable time, effort, and money...this method acceptable when used in appropriate circumstances." (Arizona Department of Water Resources 1991, 34)	Dependent on available hydrologic data, dependent on judgmental expertise; used mostly for conflict-free areas (Arizona Department of Water Resources 1991, 34)	
AQUATIC	Hydraulic Rating	1-d hydraulic models – HEC-RAS	Hydraulic parameters (Arizona Department of Water Resources 1991, 34)	Produces spatially explicit predictions (Shafroth et al. 2010, 68-85)	Lack of data reduces reliability, critical site classification subjective (Arizona Department of Water Resources 1991, 34); requires additional development of links between physical processes and ecosystem benefits (Annear et al. 2004); not appropriate for high-gradient streams and rivers (Annear et al. 2004)	unknown
AQUATIC		2-d hydraulic models	Hydraulic parameters and composite graphs (Arizona Department of Water Resources 1991, 34)	Decent analytical capabilities, model predictions provided (Arizona Department of Water Resources 1991, 34)	Cannot relate habitat to fish biomass; useful for determining "flow data for ungaged streams" but not considered a "substitute for on-site streamflow measurements" (Arizona Department of Water Resources 1991, 34)	

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AQUATIC		Hydraulic rating-Other (e.g. HEC-5)	Desktop analysis of field surveys or river gauging data (Dyson, Bergkamp, and Scanlon 2003, 118 pp.)	Produces spatially explicit predictions (Shafroth et al. 2010, 68-85)	Disregards biological information and natural flow variation (Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Katz 2006, 29-49); requires additional development of links between physical processes and ecosystem benefits (Annear et al. 2004); assumptions are made that hydraulic variables can be surrogate for habitat factors (Tharme 2003, 397-441); unreliable if based on single expert; subjective determination of site selection weakens EFRs (Dyson, Bergkamp, and Scanlon 2003, 118 pp.)	Only at study site (Dyson 2003)
AQUATIC	Habitat Simulation	Instream Flow Incremental Methodology (IFIM)	Site-specific, high-quality field data, life history information, hydrologic models (Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Annear et al. 2004; Petts 2009, 1071-1086); PHABSIM information, IFIM data analysis program (Arizona Department of Water Resources 1991, 34)	Output quality determined by HSI quality (Petts 2009, 1071-1086); integration of models allows for spatial and temporal relationships of habitat to water management (Annear et al. 2004); best method to quantify habitat flow relationships (Arizona Department of Water Resources 1991, 34)	Lack of concordance between changes in suitable habitat and fish populations, simplified approach to hydraulic habitat characterization, and lack of biological realism (Petts 2009, 1071-1086); lack of ecological predictive capacity (Tharme 2003, 397-441); uncertainty often not addressed (Dyson, Bergkamp, and Scanlon 2003, 118 pp.)	
AQUATIC		Habitat Simulation - Other	Site-specific data, habitat suitability representations (Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Annear et al. 2004)	Replicable, predictive (Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Katz 2006, 29-49)	Need to study habitat persistence to address abundance/reproduction (Locke et al 2008)	May allow regional transfer of habitat use models among rivers of similar type (Petts 2009) or may require stratified sampling to extrapolate from reaches to segments (Annear 2004)
AQUATIC	Biological Response to Flow Correlation	Correlation of flow attributes with biological characteristics .	Several years of data on biological variables, flow attributes (Annear et al. 2004); data collected for other purposes may not be suitable (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); statistical techniques may require independent time series of flow and ecological indices (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); discharge, temperature and dissolved oxygen need to be studied if water quality may change (Locke et al 2008)	Addresses flow and ecology (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); directly accounts for river characteristics (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); data quality relies on sample size, statistical power (Annear et al. 2004)	Does not capture all (i.e. non-flow related) sources of variability affecting biological response; provide general relations and trends and not much indication of tight estimates of population or habitat metrics (Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Annear et al. 2004)	Determine stream type similarity to stream used to develop model before extrapolating; should be tested first (Annear et al. 2004; Dyson, Bergkamp, and Scanlon 2003, 118 pp.)
AQUATIC		Correlation of water quality with biological characteristics				

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RIPARIAN	Hydrological event models	IHA/RVA method	Requires daily natural flow records (Annear et al. 2004); can select parameters based on local circumstances (Petts 2009, 1071-1086)	Offers range of variability for indicators (Tharme 2003, 397-441); high quality requires consideration of anthropogenic alteration of streamflow (Petts 2009, 1071-1086)	Does not address physical or biological characteristics directly such as life history flow events (Annear et al. 2004; Katz 2006, 29-49); ecological validity uncertain (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); assumes coverage of inter-annual variation by intra-annual variation (Annear et al. 2004)	
RIPARIAN	Biological Event Models	Other	Statistical analyses, hydraulic modeling, and geographic information systems for the site (Hautzinger, Hickey, and Walker 2008, 28-30)			Versatile: may be used to “predict biological outcomes of different river flows and stages” (Hautzinger, Hickey, and Walker 2008, 28-30)
RIPARIAN		HEC-EFM	Time-series of daily mean flow and stage and parameters for variables to compute statistics relevant to an ecological response (Shafroth et al. 2010, 68-85); hydraulic modeling, and geographic information systems for the site (Hautzinger, Hickey, and Walker 2008, 28-30)	If applied to Populus, recruitment box model of high quality, if used for another species, lower quality (Merritt et al 2010); produces spatially explicit predictions (Shafroth et al. 2010, 68-85)	Focus on Populus for recruitment box; model assumes coupling of river stage and groundwater decline, which may not hold along gaining river reaches, in fine-textured substrates and at sites with complex substrate stratigraphy (Merritt et al 2010)	Model should be applicable to other river systems; provides hypotheses of ecological flow responses to be tested with additional studies (Shafroth et al. 2010, 68-85)
RIPARIAN	Water budget/ Evapotranspiration studies		Remote sensing plus either ground Evapotranspiration (ET) data or remotely sensed land surface temp (Glenn et al. 2007, 139-168)	Accuracy depends on site-specific factors; sap flow techniques produce highly reliable data, if calibrated properly (Williams and Scott 2009); long term measurements increase quality, as do linkages to climate and water availability (Stromberg et al 2009c)	Heterogeneity in vegetation means flux measurements may not be represented; other factors result in error bound of 20-30%; Bowen ratio method values cannot be checked for accuracy (Glenn et al. 2007, 139-168); assumptions (in Bowen method) about energy balance introduce error (Glenn et al. 2007, 139-168; Williams and Scott 2009, 37-56)	Empirical vegetation index models cannot be used outside range of conditions were developed until proven locally (Glenn et al. 2007, 139-168; Williams and Scott 2009, 37-56)

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RIPARIAN	Water source studies	Spatial contrasts	Streamflow/groundwater availability, data on rain events, amount of water used by plants and animals, ANOVA or MANOVA modeling systems	Long term measurements increase quality, as do linkages to climate and water availability (Stromberg et al 2009c); dependent on an accurate assessment of water availability and consumption by the population studied (Snyder and Williams 2000, 227-240)	Fraction of water derived from groundwater varies between vegetation types, years, and in response to measurement error (Stromberg et al 2009c)	
RIPARIAN		Use of isotopes	Isotope levels from water in plant, soil, etc., depth to groundwater or stream water, rainfall event information, ANOVA or MANOVA modeling systems (Snyder and Williams 2000, 227-240)	Long term measurements increase quality, as do linkages to climate and water availability (Stromberg et al 2009c); dependent on an accurate assessment of water sample's isotope levels and source of water (Snyder and Williams 2000, 227-240)		
RIPARIAN	Eco-Flow response curves	Focus on physiological processes; species-level processes; community-level conditions; or ecosystem-level processes	Several years of data on biological variables, flow attributes	Choice of vegetation metric can be linked with sensitivity to short vs. long term hydrologic alteration (Merritt et al. 2010); riparian response guilds are more applicable than species-focused studies for prediction (Merritt et al 2010)	Does not capture all sources of variability affecting biological response/species distribution, thus increasing the uncertainty of predictions (Annear et al. 2004; Merritt et al 2010)	Need to be applied to locations similar to those used to develop model (Annear et al. 2004); limited transferability even in the same hydroclimatic region because they are so river-specific, unless they are based on riparian response guilds calibrated to a region, in which case they apply to streams in similar stream classes (Merritt et al 2010)
HOLISTIC	Holistic methods	Building block methodology	Models of river hydraulics, groundwater-surface water dynamics, data on biotic responses and reservoir operations simulation (Shafroth et al. 2010, 68-85)	All aspects of hydrologic regime and ecosystem are studied (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); if biotic components used in model truly reflect needs of whole system, should encompass processes and conditions necessary to sustain biota (Stromberg et al 2009c)	Expert opinion may be biased (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); constructing flow regime needs based on detailing key biological elements may omit critical flow characteristics (Tharme 2003, 397-441)	

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HOLISTIC		Holistic - Other	Team of experts (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); uses mix of available and newly acquired data in physical, biological, social science (Dyson, Bergkamp, and Scanlon 2003, 118 pp.; Katz 2006, 29-49)	Flexible, robust (Dyson, Bergkamp, and Scanlon 2003, 118 pp.); quality depends on resolution of data inputs (Poff et al 2010)	Expert opinion may be biased (Dyson, Bergkamp, and Scanlon 2003, 118 pp.)	
AQUATIC/ RIPARIAN/ HOLISTIC	Non-quantitative Methods	Distribution of flora and fauna associated with water sources (springs, riparian areas, etc.).				
AQUATIC/ RIPARIAN/ HOLISTIC		Flow-ecology response curves/ELOHA	Paired streamflow and ecological data from a region (Poff et al 2010); able to utilize data of varying resolution (Poff et al 2010); IHA (Poff et al 2010); economic, sociological, hydrologic, geomorphologic, water quality, ecological, and agricultural inputs (Conserve Online)	Quality depends on resolution of data inputs (Poff et al 2010)	Will involve scientific uncertainty because of other determinants than hydrologic alteration that aren't considered (Poff et al 2010)	ELOHA relationships should be relevant to streams of similar hydrologic and geomorphologic classification (Poff et al 2010)
AQUATIC/ RIPARIAN/ HOLISTIC		Flow-ecology response relationship description				