

Desert Flows Methodology Guidebook

Determining and Establishing Water Flows
for Riparian Ecosystems in the Deserts
of the U.S. and
Mexico

Grant Weinkam, Elia Tapia,
Susanna Eden, and
Abraham Springer
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TABLE OF CONTENTS

List of Tables.....	iv
List of Figures	v
Acronyms	vi
Executive Summary	1
Key Findings	2
Recommendations	3
Introduction	4
Section I – Methods for Determining Flows	5
What data or methods are most useful to implement environmental flows?	8
What are limitations of methods for quantifying flows?	8
What methods use depth to groundwater or surface flow data and incorporate legal requirements? ..	9
What methods incorporate links between groundwater depth and surface water flow to species abundance, age structure, and survivorship?	9
What methods seek to understand how species adapt to landscape change, climate change, and ongoing drought?	10
Are there methods that are more robust for ongoing drought?	10
Are there examples of land and water managers specifically taking climate change into account as they manage for environmental flows?	11
Section II – Strategies for Ensuring Flows	13
Who are the key players in securing flows?.....	13
What mechanisms of engagement can be used to secure flows?	15
What are successful planning or management paths for ensuring flows?	19
What barriers hinder the use of available data on environmental flows?	21
Does providing flows have to be obligatory, or can voluntary agreements secure flows?	23
Are there necessary antecedent educational or institutional conditions for securing flows?	24
Section III – Techniques and Challenges to Predicting Flows	26
What are techniques to predict when pulse flows are available and how is this information communicated among parties to provide flows?	27
Are there examples where reservoir release schedules incorporated environmental flows? How were these schedules created?	28
How do groundwater flow models predict ranges in variability of base flow associated with climate change and aquifer management?	30
How have projects incorporated flexibility or adaptive management into environmental flows?	31
What role do existing regulations or policies play in the ability to predict and provide flows?	32
What role do international agreements or partnerships have in successfully predicting and managing environmental flows?	33
Conclusions	35
References	36
Appendix: Additional Information on Methods Used to Determine Flows	A-1

LIST OF TABLES

Table 1 - Methods for Determining Environmental Flows	7
Table 2 - Key Players to Instituting Environmental Flows	15
Table 3 - Cases Where Reservoir Release Schedules Incorporated Environmental Flows	28

LIST OF FIGURES

Figure 1 - Perennial streams in the DLCC region	5
Figure 2 - Sampling in-stream suspended sediment concentration.....	8
Figure 3 - Groundwater spring discharge from the Redwall Limestone wall of the Grand Canyon	9
Figure 4 - Chiricahua leopard frog.....	10
Figure 5 – Impact of drought conditions on Lake Mead	11
Figure 6 - Decreased and lower quality surface flows can negatively impact an “overlooked economic giant”, the outdoor recreation industry	14
Figure 7 - Compound model of social learning.....	16
Figure 8 - First USGS gaging station established in 1889 on the Rio Grande in Embudo, New Mexico	18
Figure 9 - Sedimentation can cover cobble and gravel beds necessary for aquatic species nesting and survival	18
Figure 10 - Early USGS hydrographer collecting flow data at Rio Grande site	21
Figure 11 - How groundwater depletion can impact surface flows	22
Figure 12 - Near peak flow event of an ephemeral stream in New Mexico.....	27
Figure 13 - Seven day hydrograph from USGS stream gage near Mammoth, Arizona	27
Figure 14 - Glen Canyon Dam on the Colorado River, Arizona.....	29
Figure 15 - California historical and projected July temperature increase (1961-2099).....	30
Figure 16 - Lower Colorado Riverbed before and during the March 2014 pulse flow	31
Figure 17 - Former U.S. Department of Interior Secretary Salazar joins U.S. and Mexico delegations for historic Colorado River water agreement in 2012	34

ACRONYMS

AEHRA	Adapted Ecological Hydraulic Radius Approach
BBM	Building Block Methodology
CASIMIR	Computer Aided Simulation Model for Instream Flow Requirements
CONAGUA	Comisión Nacional del Agua
CROWD	Coupled Reservoir Operation and Water Diversion
DLCC	Desert Landscape Conservation Cooperative
DRIFT	Downstream Response to Imposed Flow Transformation
ELOHA	Ecological Limits of Hydrologic Alteration
EPAM	Expert Panel Assessment Method
IFIM	In-stream Flow Incremental Methodology
IHA	Indicators of Hydrologic Alteration
IUCN	International Union for Conservation of Nature
LIFE	Lotic Invertebrate Index for Flow Evaluation
MAF	Mean Annual Flow
NGO	Non-Governmental Organization
PHABSIM	Physical Habitat Simulation (System)
RHABSIM	Riverine Habitat Simulation (Program)
RHYHABSIM	River Hydraulics and Habitat Simulation (Program)
RVA	Range of Variability Approach
USBR	United States Bureau of Reclamation
USDOI	United States Department of Interior
USGS	United States Geological Survey

EXECUTIVE SUMMARY

Successful implementation of environmental flow projects depends on land and water managers having clear objectives and access to reliable data. This guidebook provides information on a variety of methods that can be utilized under different fiscal or temporal constraints to determine and implement appropriate environmental flow targets. Based on evidence from cases focused in the Southwestern United States and Northern Mexico, steps are suggested to help ensure maintenance of flows under uncertain future natural and socio-economic conditions. The importance of education and engagement to increase acceptance of environmental flows-based projects and gain key player and community buy-in is described. Limitations on using some data resources and barriers to program success are defined, along with the influence of policies and international agreements on the ability to establish and maintain environmental flows. Techniques are also provided to determine future flow events. Finally, the importance of flexible and adaptive management in project planning is highlighted as an often-critical component to long-term improvement of riparian systems in arid regions.

This guidebook was developed through review of the more than 400 articles included in the Desert Landscape Conservation Cooperative (DLCC) Desert Flows Database and interviews conducted with members of federal and state agencies and Non-Governmental Organizations (NGOs) engaged in environmental flows efforts in the DLCC geographic region that encompasses the desert regions of the Southwestern United States and Northern Mexico. Interviewees responded to a list of questions generated from the DLCC Critical Management Question One team knowledgeable of current and future stressors to the ecology and function of riparian systems in the region. The questions cover how in-stream flow targets have been determined and established, and how they can be maintained in light of future climate variability and land use change. Interview material is integrated into section responses alongside references to the literature, as similar strategies and pathways were often identified from both sources.

KEY FINDINGS

- In arid regions, there is a strong need for increased understanding and high-quality, quantitative data to determine how best to manage for current and future stressors to riparian ecosystems. Considering the strong influences that regional factors can have on the natural landscape (i.e., limited water supplies, over pumping of aquifers with dependent surface waters, extended and severe temperature increases, drought conditions, as well as land use change and population increase), many areas are in need of collaborative, long-term water resource management to prevent permanent impacts to the functions and recovery potential of desert riparian systems.
- Regardless of data needs or cost limitations, numerous methods are available to determine target flows for environmental systems.
- System-specific ecohydrological data are needed to accurately model how changes will impact surface water flows. Accurate model outputs are needed to help inform and influence policies focused on allocating appropriate water volumes for environmental flows.
- Case studies can provide valuable information to water resource managers, as they identify not only effective environmental flow programs, but also the processes and key elements needed to achieve similar successes.
- Community education on the value and purpose of environmental flows can help build enthusiasm, understanding, and long-term support for the projects.
- Involving the public or key players in monitoring programs and adaptive management actions can help increase acceptance and understanding of how the environmental flows project is helping achieve community objectives.
- Generally, there is a scarcity of inter-basin and international agreements for water management and environmental flow allocations in the region. Without these formal and informal understandings, parties can often be limited in their ability to implement environmental flows programs.
- An institutional framework or enforceable agreement may be needed to generate the cost support essential for implementing environmental flows programs.
- Limited water resource availability, future socio-economic and climatological uncertainty, and lack of trust between controlling parties is preventing the forward progress of regional water planning. Improved goodwill and trust among parties is needed to advance water management discussions and improve long-term natural landscape function.

RECOMMENDATIONS

- As arid regions are, by definition, severely water-stressed environments, **there is a strong need for increased collaboration and compromise between stakeholders and organizations** to achieve the maintenance and improvement of regional riparian system ecological integrity.
- To maximize the impact of environmental flows programs in arid regions, **discussions and decisions on how best to manage limited resources in these watersheds should take place among and between all major stakeholders**. Organizations needing to work collaboratively include governmental and non-governmental groups, multi-state basin constituents, and national and international organizations of the United States and Mexico.
- Making the effort to **choose the right suite of methods** can save time and money and provide the information necessary to populate hydrologic models used to determine appropriate flow needs of environmental systems.
- **Community education programs should accompany environmental flows projects** targeted at enhancing ecosystem functionality. In addition, **inter-sectoral community building should be established early and maintained throughout environmental flows projects** to engender relationships of trust between disparate groups.
- **Monitoring and evaluation should be part of all environmental flows projects**. Project management should adapt to new information, and stakeholders should be involved and informed of progress toward project goals.
- Since many current valuation systems continue to allow degradation of ecosystem functionality, **review and reform of regulatory and economic instruments are recommended to promote sustainable watershed development**.

INTRODUCTION

With an increasing interest in allocating water for riparian and aquatic ecosystems in the western United States (e.g., Center for the Future of Arizona, 2009; Roach, 2013; Tarlock, 2014), decision makers are incorporating available information to advocate for changes in water and land management policy (Le Quesne, Kendy, and Weston, 2010). Their success can depend on the amount and quality of that information.

As most studies on surface waters in desert regions provide only qualitative data on environmental responses to changing flows (Mott Lacroix et al., 2017), there is a need for a greater supply of high-quality, quantitative information on how aquatic and riparian systems respond to alternative flow conditions (i.e., magnitude, duration, frequency, timing and rate of change) (Poff et al., 1997). To collect, interpret, and apply these data, the utilization of appropriate methods for data collection and analysis is critical if the goal is to create accurate models or simulations that predict these response relationships.

This publication is designed to help provide guidance on the various methods used to develop and implement water and land management policy and actions that support water-dependent environments of desert regions in the United States and Mexico. The guidebook is divided into three sections for determining, safeguarding and predicting environmental flows. Each section is organized in a question and answer format, and each section starts with a list of the questions hyperlinked to each answer. Questions were pre-determined by the Desert Landscape Conservation Cooperative (DLCC) Critical Management Question Team One to cover some of the most pressing and important informational needs related to environmental flows in the region. Material was collected from articles available through the [Desert Flows Database](#) (Mott Lacroix, 2016), case study reviews, and interviews with members of local, state, and federal government agencies involved in establishing and maintaining environmental flow programs in the DLCC geographic region (Figure 1). The first section discusses how to determine environmental flow targets, focusing on the scientific methods used to determine how much water a species, genus, or system needs to survive and reproduce. The second section reviews how to safeguard flows once they are determined, through the exploration of mechanisms used to bring people together who ultimately implement flow recommendations. Finally, the third section examines techniques to predict future flows, so that flow targets can be met within existing and future socio-economic and climatological contexts.

SECTION I – METHODS FOR DETERMINING FLOWS

There are a variety of methods used to determine environmental flows across the world, and the decision of which method is most appropriate will depend on a number of factors. In arid regions, many surface waters do not flow year-round and system health and function is often heavily dependent on pulse flows or storm events. Given these unique considerations for desert landscapes, certain methods may not be appropriate at certain times of the year or along certain stretches of the stream or river. Which method is most appropriate will depend on the hydrologic and ecologic conditions of the riparian system, the amount of data needed, and the resources available.

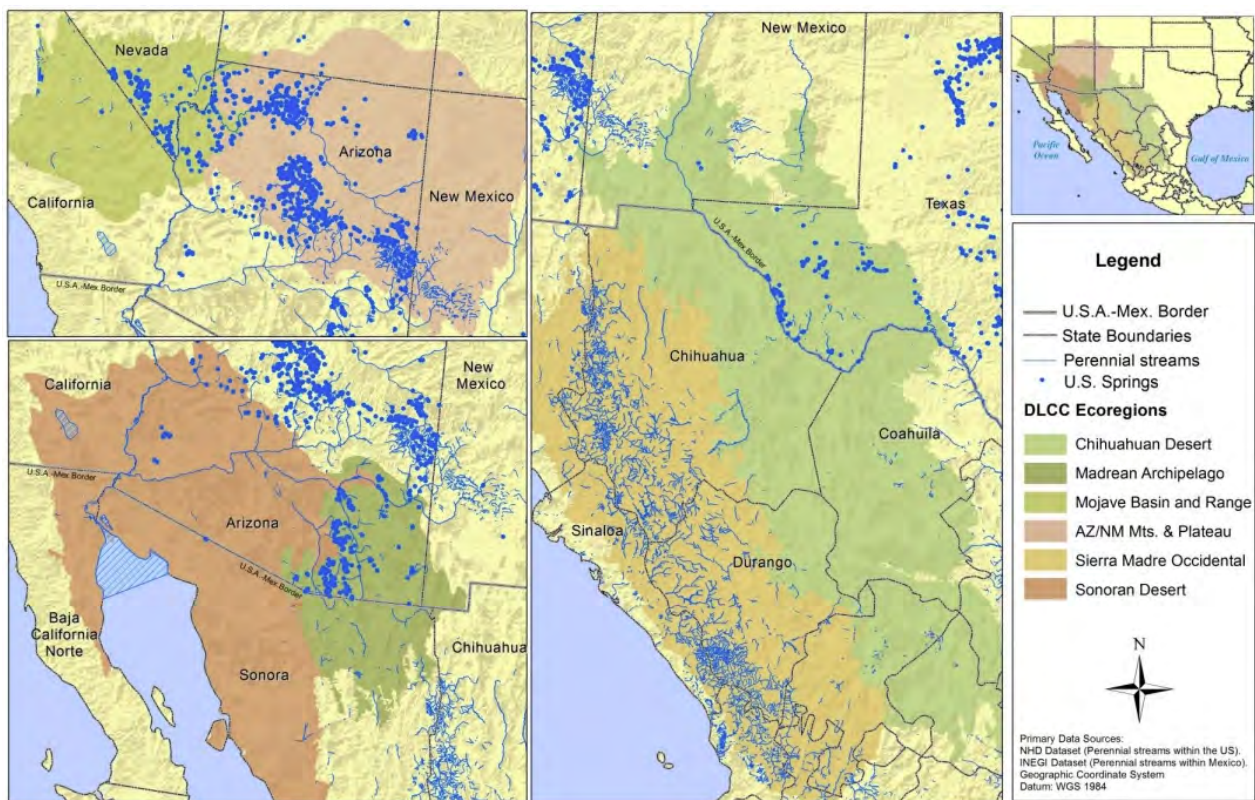


FIGURE 1 - PERENNIAL STREAMS IN THE DLCC REGION

According to a review of over 400 studies contained in the Desert Flows Database, of the thirty-four different methods recorded, 67% were described as qualitative in nature, with only 33% falling into the quantitative category (Mott Lacroix et al., 2017). Due to the lack of transferability of many of these findings, decision makers have been reliant on information that is often generalized from the needs of a particular river, stream, or spring. Because of data gaps related to system-specific understanding, Section I provides information on the most commonly applied methods to collect hydraulic, hydrologic, and ecologic data under historical and future climate

and water availability scenarios. These data are critical to informing land and water managers how their decisions will impact aquatic landscapes in the desert.

Dyson and Scanlon (2003) categorized methods into four general types for determining environmental flows. The categories all contain different initial informational requirements, use different techniques to generate data, and produce different levels of information. The four method types are: *Look-up Tables* that contain indices in tables noting target river flows; *Desktop Analysis* methods used to analyze existing data; *Hydraulic Habitat Modeling* methods to determine hydrologic impacts of flows; and *Holistic Analysis* methods that build on the understanding of the functional links between river hydrology and ecology to generate flexible, robust, and ecosystem focused outputs (Dyson and Scanlon, 2003).

Based on reviewed information and the classifications developed by Dyson and Scanlon (2003), Table 1 was generated to serve as a guide for land and water managers and others in the selection of the most suitable approach for their study. Thirty of the most common methods are organized according to method type (look-up table, desktop analysis, habitat modeling, holistic methods) and subtype (hydraulic, hydrologic, ecological). The table also includes method limitations and information on which methods are most appropriate for answering Section I key questions (listed below). For additional details review the [Appendix](#), where advantages, disadvantages, relative confidence level, and data and time requirements are provided for specific methods.

Key Questions for Section I:

- [What data or methods are most useful to implement environmental flows?](#)
- [What are limitations of methods for quantifying flows?](#)
- [What methods use depth to groundwater or surface flow data and incorporate legal requirements?](#)
- [What methods incorporate links between groundwater depth and surface water flow to species abundance, age structure, and survivorship?](#)
- [What methods seek to understand how species adapt to landscape change, climate change, and ongoing drought?](#)
- [Are there methods that are more robust for ongoing drought?](#)
- [Are there examples of land and water managers specifically taking climate change into account as they manage for environmental flows?](#)

TABLE 1 - METHODS FOR DETERMINING ENVIRONMENTAL FLOWS (MODIFIED FROM DYSON AND SCANLON, 2003)

Method Type	Subtype	Method Name	Used when minimal data are available	Used when plentiful data are available	Incorporates depth to groundwater and legal requirements	Incorporates groundwater depth, surface water flow, and species	Incorporates how species adapt to drought, landscape and climate change	Is more robust for ongoing drought	Limitations
Look-up Table	Hydrological Ecological	Flow Duration Curve							Hydrological indices not directly related to biological parameters and are not site specific (Dyson and Scanlon, 2003). Fails to preserve temporal sequencing of flows (Acreman, 2005).
		Hydrological Index							
		Natural Flow Index							
		Tennant Method							
Desktop Analysis	Hydraulic Ecological	Wetted Perimeter							Requires long time series and ecological data collection (Dyson and Scanlon, 2003). Does not reflect the full range of flow variability (Mathews and Richter, 2007). Does not consider modern eco-hydrological theories (Smakhtin et al., 2006).
		Richter Method							
		Daily Water Accounting							
		Streamflow depletion model							
		Sustainable Yield Estimator							
		Lotic Invertebrate Index for Flow Evaluation							
Habitat Modeling	Ecological	Range of Variability Approach (RVA)							Data expensive to collect (Dyson and Scanlon, 2003). Flow recommendations cannot be used for entire system (Prewitt and Carlson, 1980; cited in Tharme and King, 1998). Difficulty in needed selection of target species.
		Flow Events Method							
		Instream Flow Incremental Methodology							
		Physical Habitat Simulation Model							
		River Hydraulics and Habitat Simulation Program							
		Riverine Habitat Simulation Program							
		Computer Aided Simulation Model for Instream Flow Requirements							
		River System Simulator (RSS)							
		Riverine Habitat Assessment and Restoration Concept							
Coupled Reservoir Operation and Water Diversion (CROWD)									
Holistic Analysis	Hydrological-hydraulic-ecological	Expert Panel Assessment Method							Data expensive to collect and a need to employ a variety of experts (Dyson and Scanlon, 2003). Judgment based on a variety of people, thus results may be subjective and consensus may not be reached (Tharme and King, 1998).
		Adapted Ecological Hydraulic Radius Approach (AEHRA)							
		Building Block Methodology (BBM)							
		Holistic Approach							
		Habitat Analysis and Water Flow Restoration Methodology							
		The River Babingley Method							
		Ecosystems Function Model							
		Indicators of Hydrologic Alteration							
		Ecological Limits of Hydrologic Alteration							
		Downstream Response to Imposed Flow Transformation (DRIFT)							

WHAT DATA OR METHODS ARE MOST USEFUL TO IMPLEMENT ENVIRONMENTAL FLOWS?

The most useful data and methods for implementing environmental flows include historic flow values and the accurate projection of future conditions under alternative environmental (e.g., temperature, precipitation, evapotranspiration) and human development scenarios.

When minimal data are available, *Look-up Tables* can be a fast and cost-effective approach to determining flow requirements. Other methods highlighted in Table 1 can also be used to provide worthwhile information when data limitations exist. Depending on the method chosen, data requirements for look-up tables may range from low to moderate, and typically take about two weeks to complete (Hirji and Davis, 2009). Calculations for how to conduct the methods can be found in Dyson and Scanlon (2003).

Case studies can also provide a clear process on how to get started and move forward. Pulse flows experiments, for example, can provide information on the accuracy of model simulations, validation of the methods used, and answer how effective flow modifications were at achieving stated objectives. Additional information is available in [Section III](#).

Combining techniques can also yield valuable outputs. Some examples can include:

- Hydraulic and hydrologic modeling combined with ecological outcomes;
- Flow modeling combined with water quality modeling;
- Multi-criteria decision making, where modeling results are interpreted in terms of indicators that all decision makers have understood and agreed upon;
- Environmental monitoring programs integrated with adaptive management.



FIGURE 2 - SAMPLING IN-STREAM SUSPENDED SEDIMENT CONCENTRATION. LITTLE COLORADO RIVER NEAR DESERT VIEW, ARIZONA. (PHOTO CREDIT: USGS)

WHAT ARE LIMITATIONS OF METHODS FOR QUANTIFYING FLOWS?

Over recent decades different methods for determining environmental flows have been developed, with most facing some sort of criticism (Alcazar, 2010). Some can be considered subjective or incomplete, while others ignore ecological relationships and focus solely on hydrologic data. Other methods are well-established, but require a lot of data that are unavailable or expensive to collect. The last column of Table 1 provides a summary of the common limitations for method types.

It can also be difficult to accurately predict how natural and human induced changes will impact future flows. One example of a chain of events that influenced flow behavior was the upgrading of the Nogales International Wastewater Treatment Plant that discharges effluent into the Santa Cruz River (Arizona). Upgrades to the plant decreased effluent nutrient concentrations, resulting in decreased nitrogen and phosphorus loading to the river. Reduced surface water nutrients resulted in decreased growth of the benthic layer of algae and microorganisms, or “Schmutzdecke”, that had been inhibiting groundwater infiltration from the riverbed. Unless changes such as this are explicitly predicted to occur in flow estimates, methods can be limited in their ability to accurately predict infiltration, groundwater recharge, and surface water flow rates.

WHAT METHODS USE DEPTH TO GROUNDWATER OR SURFACE FLOW DATA AND INCORPORATE LEGAL REQUIREMENTS?

Although there is not much information on methods that combine hydrological conditions with legal requirements, we include holistic methods under this category as they include information on hydrology, hydraulics, ecology, and social aspects that can include legal mandates.

Holistic approaches such as the Downstream Response to Improved Flow Transformation (DRIFT) assessment method can be used as a fully comprehensive technique for determining in-channel and floodplain watering under different development scenarios.



FIGURE 3 - GROUNDWATER SPRING DISCHARGE FROM THE REDWALL LIMESTONE WALL OF THE GRAND CANYON. ACCURATE ESTIMATES OF GROUNDWATER INPUTS TO SURFACE WATER SYSTEMS CAN IMPROVE PROJECT SUCCESS. (PHOTO CREDIT: USGS)

WHAT METHODS INCORPORATE LINKS BETWEEN GROUNDWATER DEPTH AND SURFACE WATER FLOW TO SPECIES ABUNDANCE, AGE STRUCTURE, AND SURVIVORSHIP?

According to Hughes and Pauline (2003), the Building Block Methodology (BBM) links groundwater depth or surface water flows to species in terms of their habitat requirements. In any approach, magnitude, duration, timing, and frequency of flows should be considered for determining the appropriate environmental flow regime. The incorporation of the Expert Panel Assessment Method (EPAM) can strengthen efforts. Utilization of this expert panel method allows for the determination of system baseflow requirements, through the incorporation of

hydrological indices, cross-section based hydraulic data, and information on the flow-related needs of ecosystem components (Tharme and King, 1998). The use of the BBM and EPAM were key components for determining environmental flow targets in five sub-basins in the binational Rio Conchos watershed in Chihuahua, Mexico from 2006-2008 (Rodríguez-Pineda, 2013).

WHAT METHODS SEEK TO UNDERSTAND HOW SPECIES ADAPT TO LANDSCAPE CHANGE, CLIMATE CHANGE, AND ONGOING DROUGHT?

Holistic analyses relate hydrological, hydraulic, and ecologic information to determine the environmental flows needed to meet the different aspects of the riverine system. For example, the River Babingley Method uses environmental flows benchmarks such as “Threshold”, “Adequate”, “Desirable” and “Optimum” ecological flows and can be related to landscape, climate change, and ongoing drought. This method is similar to the BBM and Holistic Approach, which also seek to understand how species adapt. For additional information on regional projects focused on providing scientific information, tools, and techniques to anticipate, monitor, and adapt to climate change, visit the collaborative University of Arizona and U.S. Department of Interior (US DOI) [Southwest Climate Science Center](#).



FIGURE 4 - CHIRICAHUA LEOPARD FROG. THIS VULNERABLE SPECIES, NATIVE TO MEXICO, ARIZONA, AND NEW MEXICO, IS DEPENDENT ON DESERT SPRINGS AND SURFACE FLOWS FOR SURVIVAL AND REPRODUCTION. (PHOTO CREDIT: USFWS)

ARE THERE METHODS THAT ARE MORE ROBUST FOR ONGOING DROUGHT?

Methods that can incorporate changing and extreme boundary conditions for climate are best for ongoing drought planning. Hydrologic indices related to predictability, constancy, and seasonality of monthly flows can be difficult to accurately predict but important to planning efforts. The holistic analysis approaches that include the BBM, the River Babingley Method, and the Holistic Approach Method can be applied under these circumstances and utilized in ongoing drought scenario planning (Tharme and King, 1998). To account for some of the inherent variability of the system, the BBM incorporates four blocks of monthly values for determining flow conditions in drought years, two under low or base flows and two under high or pulse event flows (Hughes and Pauline, 2003). The River Babingley Method also includes provisions for wet years and drought conditions (Tharme and King, 1998). Water managers in the region are increasingly taking drought adaptation into account to better manage system performance.

ARE THERE EXAMPLES OF LAND AND WATER MANAGERS SPECIFICALLY TAKING CLIMATE CHANGE INTO ACCOUNT AS THEY MANAGE FOR ENVIRONMENTAL FLOWS?

While surface flow forecasting models are available, climate change is not incorporated into short-term predictions in most cases. Climate variability can, however, be incorporated into long-term planning scenarios. Local, regional, and federal policies related to the acceptance or denial of climate change can also influence the robustness and applicability of models used to plan for future climate conditions.

One method that can be used involves the comparison and review of aquatic conditions during historical drought events. In these cases, a practitioner uses drought years as a proxy for understanding what conditions may be like under future climate conditions. Aerial photos and stream flow data during droughts of the past century can provide valuable information into how systems may respond in the future.



FIGURE 5 – IMPACT OF DROUGHT CONDITIONS ON LAKE MEAD. BETWEEN 2001 (LEFT) AND 2015 (RIGHT) THE LAKE ELEVATION DROPPED FROM 1,196 TO 1,075 FEET, A DECLINE OF 121 FEET. LONG-TERM IMPACTS OF EXTENDED DROUGHT CONDITIONS ON COLORADO RIVER RELIANT SYSTEMS ARE UNCERTAIN. (PHOTO CREDIT: US DOI)

Additional methods currently being implemented can be gathered from the [Moving Forward Effort on the Colorado River Basin](#) (Phase 1 completed in May 2015). This forward-thinking initiative addresses ongoing and future water supply and demand challenges and presents information from stakeholder workgroups focused on (1) municipal and industrial water conservation and reuse programs, (2) agricultural water conservation, productivity, and transfers, and (3) environmental and recreational flow needs. It also contains additional

resources, including efforts to develop climate analysis tools that take into account climate change impacts on water resources and help inform decision makers (USBR, 2017).

In another example, Montana’s Department of Natural Resources and Conservation [Yellowstone River Basin Water Plan](#) explicitly references how climate change and drought will affect environmental flows and how well situated the river system is in terms of “drought readiness” (Montana DNRC, 2014, pp. 58-66, 160).

As data and trends related to climate shifts continue to become more clearly understood, temperature and precipitation predictions will become increasingly reliable. This advance in fundamental understanding will inevitably provide land and water managers with new cost-effective tools for meeting a basins’ environmental flow needs under long-term future water resource uncertainties.

SECTION II – STRATEGIES FOR ENSURING FLOWS

Once surface water volume and timing goals are determined, environmental flows then need to be implemented and safeguarded. This can be especially challenging in arid regions, as socio-economic pressures for maximizing the use of water outside of the river channel can be significant. In many over-allocated and water-stressed basins a socio-political landscape can be present where the lack of policies and agreements among regional interests on environmental flows can result in the failure to achieve flow goals. To address these concerns, this section examines the relationships and activities that can influence flows over space and time, the mechanisms that bring together the people who ultimately implement flow recommendations, and techniques used to help secure environmental flows.

Key Questions for Section II:

- Who are the key players in securing flows?
- What mechanisms of engagement can be used to secure flows?
- What are successful planning or management paths for ensuring flows?
- What barriers hinder use of available data on environmental flows?
- Does providing flows have to be obligatory, or can voluntary agreements secure flows?
- Are there necessary antecedent educational or institutional conditions for securing flows?

WHO ARE THE KEY PLAYERS IN SECURING FLOWS?

As water conflicts are multidimensional, active partnerships among scientists, land and water managers, policy makers, and regional stakeholders are necessary for transcending hostility and achieving project success. When all parties affected by changing flow regimes are included in the decision-making process, critical tasks, such as problem definition and goal setting, can be conducted in a more collaborative and efficient manner. This type of inclusive planning can lead to greater success in achieving project goals (IUCN, 2000; Macleod, 2007; Poff, 2003).

The major players will depend on the specific bio-physical and socio-economic conditions within a basin. Bio-physical considerations can include availability of water resources or the presence of endangered or sensitive species. Socio-economic variables can include land use change and development trends and water needs for residential, commercial, industrial, and agricultural sectors. Certain organizations and agencies may also have responsibilities for water resource management, such as conducting or promoting monitoring, water infrastructure maintenance, and public education (Acreman, 2005). Table 2 displays examples of organizations that can play key roles in ensuring environmental flows and can be used as a preliminary checklist of potential partners able to provide informational, technical, and/or financial support.

In the United States, it may be important to involve federal level agencies, such as the Environmental Protection Agency, the Bureau of Reclamation, and the Fish and Wildlife Service. However, as water in the United States is managed primarily on state and local levels, there is also a plethora of other potential key players, including state regulatory and resource agencies, municipal, county, and tribal governments, semi-governmental organizations such as irrigation districts, control boards, and non-governmental entities. Community-based organizations, educational and research institutions, donor organizations, local landowners, and constituents of the outdoor recreation industry should also be considered.

In Mexico, the national water commission, known as Comisión Nacional del Agua (CONAGUA), plays a leading role in water-related issues. All surface water and groundwater are national property and can only be used through a state concession or permit. Procedures for ensuring water for environmental flows (norm NMX-AA-159-SCFI-2012) were published in 2012, but their application is not obligatory.

Cooperation among CONAGUA, other government agencies, and local stakeholders is needed to address regional problems involving Mexico. The binational Rio Conchos basin, which flows from the state of Chihuahua, Mexico to the Rio Grande near Presidio, Texas, is one example of riparian system degradation caused by anthropogenic activities, climate stresses, over-allocation of surface and groundwater, and untreated wastewater and irrigation discharges. To address these water resource challenges, more than fifty experts from eighteen government agencies, numerous academic institutions, and local communities all came together to determine the long-term environmental flow needs of the system (Rodríguez-Pineda, 2013).

In another example from Mexico, the proposed Independence Aqueduct, a project to transfer water from el Novillo Dam to Hermosillo in the state of Sonora, raised concerns related to environmental flows in the Rio Yaqui. Substantial disagreements with the proposed project resulted in the formation of the “No al Novillo” movement, where public outcry and protests resulted in a court ordered study to take into account available information on precipitation, stream flow, water uses, and the hydrologic methods used to make the initial decision (Barry, 2015).



FIGURE 6 - DECREASED AND LOWER QUALITY SURFACE FLOWS CAN NEGATIVELY IMPACT AN “OVERLOOKED ECONOMIC GIANT”, THE OUTDOOR RECREATION INDUSTRY. IN 2012, 56% OF ARIZONA RESIDENTS PARTICIPATED IN OUTDOOR RECREATION, SPENDING OVER \$10.5 BILLION (OIA, 2012). (PHOTO CREDIT: US DOI)

TABLE 2 - KEY PLAYERS TO INSTITUTING ENVIRONMENTAL FLOWS

Key Players	Specific Examples	Notes
Federal government	Dept. of Energy; Dept. of Interior; Fish and Wildlife Service; Environmental Protection Agency; Dept. of Agriculture; U.S. Geological Survey; CONAGUA	Other examples: Federal Energy Regulatory Commission; U.S. Forest Service; Bureau of Reclamation; Bureau of Land Management; National Resources Conservation Service; DLCC
State government	Departments of: Natural Resources; State Lands; Water Resources; Fish and Game; Environmental Quality; Agriculture	Departments issue water rights permits and have basin focused employees able to provide technical and financial support
Local governments; communities; landowners	Cities and towns; counties; neighborhood groups; individual landowners and agricultural operators; cattleman’s association	High levels of engagement with basin stakeholders and community members is critical to project success
Indigenous tribes	Tribal governments; native communities; landowners	Need to be engaged if their water supply will be affected
Surface water control entities	Utilities; dam operators; water control boards; irrigation districts	Reservoir operation and release schedules influence downstream hydrologic function
Non-governmental organizations	Conservation groups (The Nature Conservancy); watershed partnerships (Arizona Riparian Council); community based forestry organizations; other politically or economically-based NGOs	Organizations focused on landscape management and riparian restoration can assist at various stages in project development
Industry	Mines; agricultural producers; ranchers; outdoor recreation industry	Need to be engaged if there are impacts to/from industrial water supply or water quality
Donor agencies	Walton Family Foundation; FishAmerica Foundation; William and Flora Hewlett Foundation; American Rivers; Environmental Defense Fund	Can provide support appropriate to the region and goals
Technical/educational institutions	Professionals in social and natural science fields at universities, colleges, and environmental consultancies	Can provide legitimacy and validity to approach, predicted outcomes, monitoring, and recommendations

WHAT MECHANISMS OF ENGAGEMENT CAN BE USED TO SECURE FLOWS?

Stakeholder engagement is critical for a project to be successful. Below are suggested methods of engagement that bring out and reinforce values associated with integrated watershed management and environmental flows. Many of these techniques can influence an important aspect of project success, termed “social learning”, or the process in which individuals co-create knowledge and mutual understanding and modify their behavior (Figure 7) (Muro, 2008; Pahl-Wostl, 2006; Reed et al., 2010).

COMMUNITY PARTICIPATION AND AWARENESS

An instream flow program needs public confidence or a heartfelt belief that the program will achieve its goals for it to be successful (Katz, 2006). Clear objectives, careful planning, and attention to details related to methods, goals, and strategies are all conducive to increased community buy-in of the project.

Participation among the various community, government, and water using sectors is vital for sustained success in restoring and maintaining environmental flows. Stakeholder buy-in is important not only in the initial stages of project design and implementation, but also into the future, given the uncertainty of events related to reduced water availability (i.e., drought and declining aquifer levels) or increased water demands (i.e., growth and development).

Some organizations trying to incorporate community participation, such as watershed partnerships, have found challenges in recruiting and sustaining members. To increase enthusiasm and awareness of ongoing projects, practitioners have found that increased monitoring with more regular communication of results to stakeholders to be an effective strategy (Fernandez, 2008).

Additionally, greater understanding among participants can be achieved and ultimately improve rates of success when monitoring is conducted with collaborative teams. Involving diverse and even adversarial interest groups at key points in the monitoring process can help resolve conflicts and advance overall understanding of the interdependence of human and natural systems. These practices can build trust internally and credibility externally, while fostering social learning and community-building (Fernandez, 2008; Pahl-Wostl, 2006).

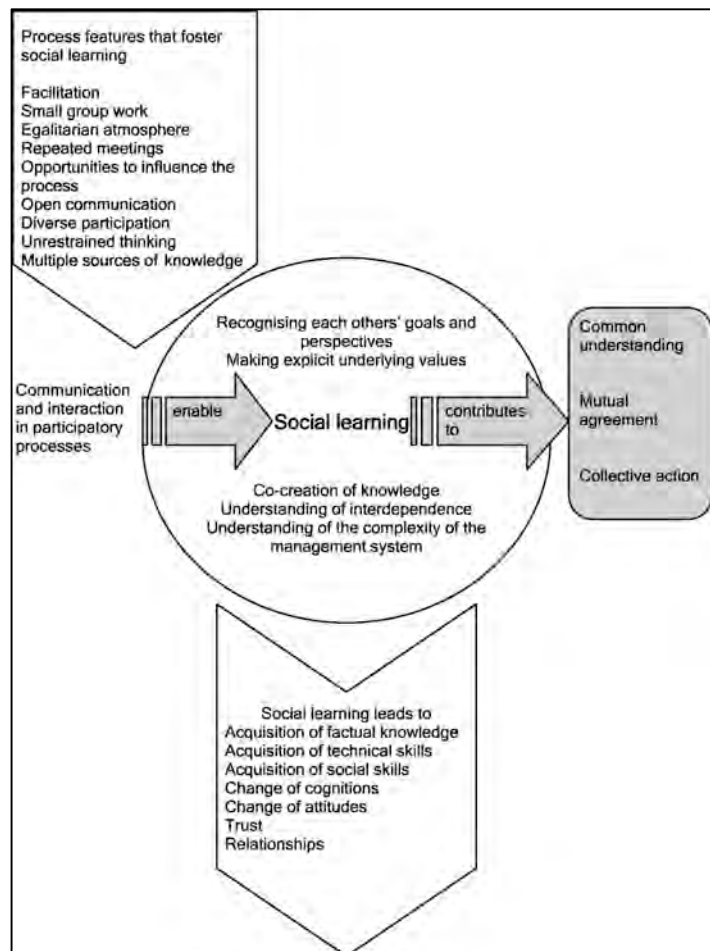


FIGURE 7 - COMPOUND MODEL OF SOCIAL LEARNING (MURO, 2008)

TRANSFERABLE STRATEGIES FOR SECURING AND MAINTAINING FLOWS

- **Employ early-stage collaborative engagement and training events** with scientists, managers, stakeholders, and the general public to increase support and understanding of the project. Training sessions should focus on environmental flow concepts and best practices, as some communities and organizations have limited or no experience with principles of environmental flows (Hirji and Davis, 2009).
- **Form steering committees and use them throughout the project** to have continued local involvement in project development.
- **Highlight how ecological processes in healthy riparian systems can provide social and economic benefits** (Everard, 2004). Give specific examples where social and economic measures have demonstrated the value of water for the environment. Integrating these benefits into preliminary and long-term plans can achieve greater buy-in and acceptance of upfront costs associated with the projects. This approach has been found to be effective in Mexico and Latin America (Hirji and Davis, 2009).
- **Involve stakeholders in the use of hydrologic and hydrogeological models** to predict water savings, water use, and impacts to downstream ecological systems.
- **Establish relationships between educational institutions** to ensure that the needed diversity of expertise is met.
- **Investigate market-based trading or water swaps to create win-win exchanges**, such as was used on the Rio Grande (Colorado Parks and Wildlife Commission, 2014; Douglas, 2009; Rio Grande Basin Roundtable, 2015), the Yakima River in Washington (State of Washington Department of Ecology, 2017; USBR, 2011, 2012), and the Platte River in Colorado and Nebraska (Colman, 2017).
- As funding is required for market transfers of environmental flows (Loehman, 2011), **develop new and innovative funding partnerships** to execute monitoring programs and conduct infrastructure upgrades needed to implement transfers. New partnerships also increase the stakeholder base of support for on-going efforts.
- **Take lessons from large-scale river experiments**, as regional cases can provide positive encouragement and interest in future projects (Poff, 2003).

HISTORICAL DATA FROM UNIMPAIRED SYSTEMS

Environmental flow targets should be based on natural flow regimes of undisturbed systems. Unfortunately, this information is typically limited to gaging stations on minimally altered rivers or previously studied cross-sections of unimpaired river stretches (Figure 8). Alternative methods are often needed to fill a lack of important historical or observational data. Empirical and statistical methods are often useful to fill these data needs. Table 1 (Section I) provides information on suggested approaches to collect data when historical or pre-disturbance values are not available. This information can be useful in helping people understand a waterway's historical condition.



FIGURE 8 - FIRST USGS GAGING STATION ESTABLISHED IN 1889 ON THE RIO GRANDE IN EMBUDO, NEW MEXICO. (PHOTO CREDIT: USGS)

PROVIDING INFORMATION ON HOW FLOW CHANGES CAN INFLUENCE SPECIES SURVIVAL

Information linking hydrographs to the life cycles of biota can be important to determine whether the designed plan will provide ideal habitat for target species throughout the year. Specific variables that can drive success can include not only the presence of water, but also depth, temperature, velocity, substrate, and cover (Figure 9). Changes in these factors over seasons, and the need for low-flow and/or high-flow events, will determine whether project goals are achieved. Methods that incorporate ecological considerations are listed in Section I.



FIGURE 9 - SEDIMENTATION CAN COVER COBBLE AND GRAVEL BEDS NECESSARY FOR AQUATIC SPECIES NESTING AND SURVIVAL. PULSE FLOWS OF VARYING INTENSITY CAN HELP REDISTRIBUTE SEDIMENT, FLUSH ACCUMULATED SALTS, AND REPLENISH NUTRIENTS IN THE FLOODPLAIN. (PHOTO CREDIT: USGS)

APPROACHES FROM AROUND THE UNITED STATES AND MEXICO

While not a complete list, hyperlinked below are some approaches that have been used to develop and apply environmental flow criteria. The Nature Conservancy report, “A Practical Guide to Environmental Flows for Policy and Planning” (Kendy, 2012) provides additional information on a number of these cases.

- [California Department of Fish and Wildlife Instream Flow Program](#)
- [Colorado Watershed Flow Evaluation Tool](#)
- [Connecticut Statewide Environmental Flow Regulations](#)
- [Connecticut River Basin Ecosystem Flow Restoration](#)
- [Glen Canyon Dam Adaptive Management Group \(Arizona\)](#)
- [Massachusetts Sustainable Water Management Initiative](#)
- [Michigan’s Water Withdrawal Assessment Process](#)
- [Mexican Environmental Flow Standard \(Gómez-Balandra, 2014\)](#)
- [Middle Potomac River Basin Environmentally Sustainable Flows \(Maryland\)](#)
- [Ohio Thresholds for Ecological Flow Protection](#)
- [Rhode Island Stream Depletion Method](#)
- [Susquehanna River Basin Ecosystem Flow Recommendations \(New York/Pennsylvania\)](#)
- [Texas Commission on Environmental Quality E-Flows Program](#)
- [Texas Living Waters Project](#)
- [Washington State Department of Ecology Instream Flows Initiative](#)

WHAT ARE SUCCESSFUL PLANNING OR MANAGEMENT PATHS FOR ENSURING FLOWS?

A number of cases to ensure environmental flows have showcased success in planning and management. Some aspects of these efforts can be replicated, while others are specific and dependent on the resource base, political climate, and environmental interests of the region. Local water resource affiliated agencies and organizations currently implementing environmental flows projects within the specific basin of interest can provide examples of success ([see Table 2](#)). Additional cases where techniques were implemented to establish environmental flows in reservoir controlled rivers can be found in [Section III](#).

PARTNERSHIPS AND FUNDING SUPPORT

Because large-scale river systems often fall across geopolitical boundaries, collaboration between governmental and non-governmental basin stakeholders is required (Lebel et al., 2005). Engaged consultative committees, made up of members from all sectors, can help drive a project that maintains a sense of community ownership. Strong community acceptance can also be

promoted when goals target protecting specific species of interest (Hirji and Davis, 2009). Private or federal/state water improvement grant funding can help support work targeted at restoring and protecting aquatic habitats, education to foster stewardship, and informational visitor centers.

UNDERSTANDING AT THE MANAGEMENT LEVEL THE RELEVANCE OF ENVIRONMENTAL FLOWS AND THE PROCEDURES USED TO ESTABLISH FLOW TARGETS

The need to maintain minimum flows in sensitive systems is a rationale that can be emphasized to drive project support. Agreement on the value of minimal flows can open the door to further discussion of achieving specific goals necessary for species and systems to survive and thrive. One example occurs through the Montana Board of Natural Resources and Conservation, which applies the “maintenance of minimum flows” method to the Yellowstone River, one of the country’s last remaining free-flowing systems (Montana DNRC, 2014).

In over-allocated basins, options may be limited to the reorientation of available water resources. Low cost options may include water conservation programs, rain water harvesting, or the augmentation of groundwater and surface waters through storm water and treated wastewater recharge basins.

COST VALUATION OF ALLOCATING WATERS TO ENVIRONMENTAL SYSTEMS

Recognition of the direct and indirect values achieved through basin management and restoration efforts can help raise support for environmental flows projects. In calculating the total benefit-to-cost ratios for river restoration projects in England, Everard (2004) showed a return on dollars invested ranging from 1.6:1 to 8.2:1, depending on the river system. These investments were found to add upwards of \$10 million of quantified benefits to the basin. However, this study did not incorporate “unquantified benefits”, which can have a substantial impact to the overall value of the project. Unquantified benefits of projects can include: direct and indirect socio-economic benefits, increased biodiversity and species numbers, changes in aquifer levels, and improved long-term water resource sustainability. Some unquantified benefits specific to rural communities can include: alleviating rural poverty, providing for rural sustainability, enhancing regional distinctiveness, and supporting adaptation to changing circumstances. The quantification and incorporation of such figures into project proposals can help further justify the costs of allocating flows for river restoration and maintenance.

NEED FOR MONITORING, DATA ASSESSMENT, AND ADAPTIVE MANAGEMENT

Monitoring data have been identified as critical for long-term success and acceptance of projects. Government and non-governmental groups can collaborate to minimize data redundancy and lower overall monitoring costs. In one example, [The Nature Conservancy's Wet/Dry Mapping of Desert Streams Program](#) utilizes volunteers and citizen scientists in the collection of data in rivers with interrupted perennial surface flows. The program, which involves people walking or riding horses along desert streams to map hydrologic conditions with hand-held GPS units, presents a low-cost, comprehensive, and enjoyable method to get the community involved in local monitoring programs. This information can then be used for enforcement and adaptive management purposes. Assessing the data on an on-going basis allows for adjustment and alteration of original plans and ultimately improves success rates. Additional information on adaptive management pathways can be found in [Section III](#).

WHAT BARRIERS HINDER THE USE OF AVAILABLE DATA ON ENVIRONMENTAL FLOWS?

The primary barriers to using previously collected flow data are related to limitations in scientific data, lack of key player knowledge about system interconnectivity, and financial support.

LIMITATIONS ON THE QUALITY AND RELIABILITY OF DATA

While data may be collected using valid, accurate, and appropriate methods, often techniques for ecological research often present a mismatch of scale between the spatial extent of the research (e.g., an isolated stream or river section) and the spatial extent of management decisions. It can also be difficult to accurately extrapolate findings, as geo-political boundaries rarely align with watershed boundaries (Arthington, 2006; Grayson and Blöschl, 2001; Lebel et al., 2005).

Some managers may be concerned that methods developed and calibrated in more humid environments may not yield accurate results in arid regions. There is a need for increased observation and monitoring to confirm the validity of methods developed outside of desert landscapes. For some

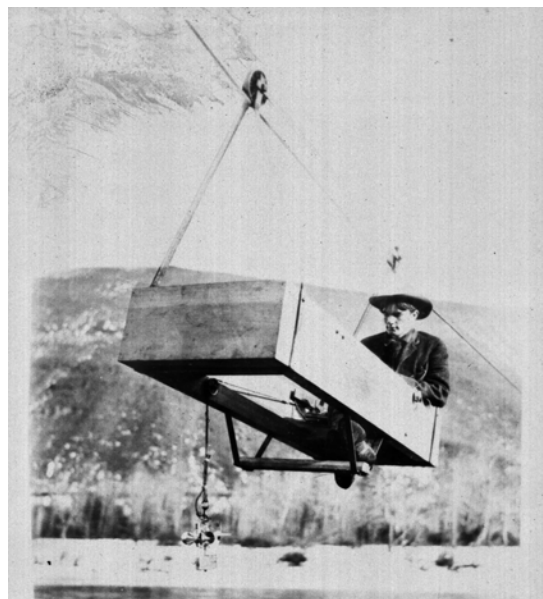


FIGURE 10 - EARLY USGS HYDROGRAPHER COLLECTING FLOW DATA AT RIO GRANDE SITE. CONSISTENCY OF DATA COLLECTION METHODS IS IMPORTANT TO ACCURATELY ASSESSING HOW CLIMATE VARIABILITY AND ANTHROPOGENIC INFLUENCES HAVE AND WILL IMPACT SURFACE FLOWS. (PHOTO CREDIT: USGS)

stakeholders, there can also be a general uneasiness with the use of models and associated outputs that are perceived to be derived from methods defined as “environmental” or “ecological” in nature. Utilization of a variety of verified methods can help alleviate these concerns.

LIMITATIONS CAUSED BY ASSUMPTIONS

To conduct model simulations that predict the future status of water resources in a basin, certain assumptions must be made. These assumptions, and how they are incorporated and weighted in the models, can influence the applicability and accuracy of forecasted results.

Influential variables can include:

- Climate trends;
- Population and land use change;
- Management practices;
- Dam release volume and timing;
- Agricultural return flow rates;
- Reclaimed wastewater fate;
- Changes in water/land use law.

LIMITATIONS IN KNOWLEDGE ABOUT THE INTERCONNECTIVITY OF GROUNDWATER AND SURFACE WATER SYSTEMS

A lack of understanding as to how groundwater and surface water are interconnected can cast doubt on the value of previously collected data. Increased stakeholder education on how changes to one portion of the system (e.g., lower aquifer levels) can affect another portion (e.g., decreased surface water flows) can lead influential parties to acknowledge system interactions (Figure 11) and develop a greater understanding of why the maintenance of both ground and surface water sources is important (Douglas, 2009).

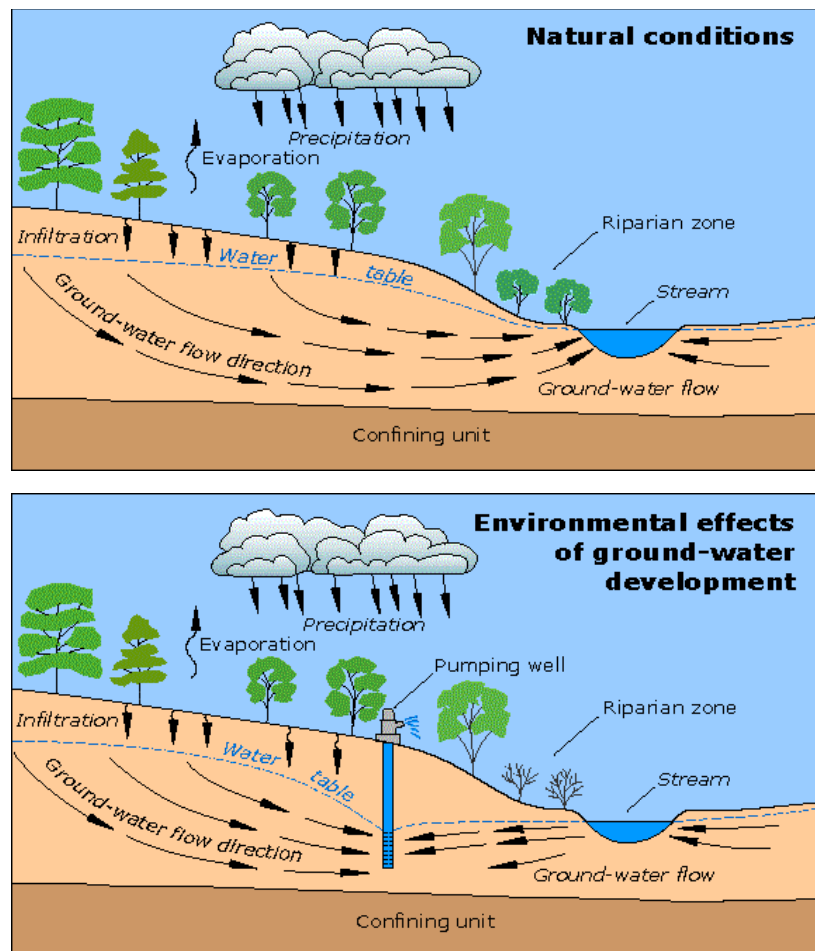


FIGURE 11 - HOW GROUNDWATER DEPLETION CAN IMPACT SURFACE FLOWS. UNDERSTANDING OF HYDROLOGIC PRINCIPLES CAN HELP PROMOTE INTEGRATED WATER RESOURCE MANAGEMENT.

(IMAGE CREDIT: USGS)

A LACK OF UNDERLYING AGREEMENTS AND COST SUPPORT

For some environmental flow programs to be executed, there is a need for the appropriate legislation, agreements, and cost support to be in place. Additional information on this subject can be found in [Section III](#). Issues that may need to be resolved can include:

- A need for treaties or other agreements between nations or governmental/community organizations to achieve desired flows;
- Cost support for retrofitting dams or redesigning outlets to accommodate target flows;
- Enforcement of flow agreements;
- Performance audits investigating the effectiveness of instream flow policies.

DOES PROVIDING FLOWS HAVE TO BE OBLIGATORY, OR CAN VOLUNTARY AGREEMENTS SECURE FLOWS?

In regions where water resources are plentiful, voluntary agreements can work well to secure flows. In water-scarce environments, however, where water is often closely tied to current and future economic viability of a region, enforceable water use agreements may be necessary (Acreman, 2005; Douglas, 2009). These agreements do not need to be state or federally sanctioned, but must have a reasonable means of enforcement if conducted among environmental, agricultural, industrial, and municipal interests.

As recourse to regulations can dissuade initial project buy-in, voluntary short-term agreements may be the first step to get parties to agree to environmental flow allocations. Preliminary, voluntary agreements that acknowledge a need for data collection and adaptive management can be a successful approach to gaining key player participation.

In cases from around the world (e.g., Senegal (Hirji and Davis, 2009); Berg River in South Africa (Tharme and King, 2008)) researchers found that land and water managers can be reluctant to accept the concept and institutionalization of environmental flows until formal legislation and/or water charters have been agreed upon. In other cases, (e.g., Aral Sea in Kazakhstan and the Tarim Basin in China) the need to restore the “green corridor” was unquestioned due to dramatic changes in the function and quality of the system (Hirji and Davis, 2009).

If all parties cannot come to an agreement on what are fair and equitable distributions of the water resources, environmental flows may depend on interventions by authorities at the local, state, and/or federal level.

ARE THERE NECESSARY ANTECEDENT EDUCATIONAL OR INSTITUTIONAL CONDITIONS FOR SECURING FLOWS?

Necessary antecedent social conditions begin with public and government recognition of the need for water resource protection. In cases from around the world, encouragement for environmental flow allocations has been spurred on by either incremental decreases in system flow rates over time or extreme weather/climate events. In water-stressed regions, numerous cases can be pointed to where historically perennial streams now only flow in response to intense precipitation events. Support for regional projects can be strong, given the presence of significant flow rate changes and extended drought conditions that will impact riparian landscapes into the extended future.

A report by the International Union for Conservation of Nature (2000) acknowledged the need for people to better understand how human and environmental systems are intricately linked:

“In order to want to act for environmental conservation, people must attain a general level of understanding of, and caring for, ecosystem functions and benefits (e.g., the water cycle, the role of catchment protection for drinking water and aquatic life, the biodiversity of freshwater systems, and the relationship between land-based activities and marine and coastal zones). Education, training and capacity building will put people in a better position to make informed choices and act to conserve the resources within their catchment area.” – IUCN, 2000

“Primary and secondary education are the cornerstones of modern societies. The integration of environmental learning into school curricula – for example, information about the goods and services provided by ecosystems, the richness of species in rivers, lakes and coastal areas, and the cause-and-effect relationship between human actions and environmental conditions – forms the basis for environmental awareness and environmentally-responsible behavior, now and in the future.” – IUCN, 2000

If local stakeholders are not the driving force behind changing water policy for environmental flows, government agencies, environmental advocacy groups, scientific organizations, or academic institutions may lead the process. These organizations can also develop curricula and training programs to improve community understanding and, ultimately, regional capacity for freshwater and riparian ecosystem management.

Community members can benefit from better understanding how environmental flow allocations can be of value and how alternative flow regimes can influence natural, cultural, and socio-economic resources in the community and beyond. This community understanding has been identified as critical for the success of efforts to achieve efficient water use (Kendy, 2012). Additional subject matter that can help increase overall understanding can include: climate related data trends, value and limitations of water resources, and how instream flow measurements are conducted and interpreted. It can also be important for people to better comprehend what is meant by the terms “scientific uncertainty” and “adaptive management.”

Individuals who are willing to pay for environmental flows can support flow restoration or protection. Receptiveness towards willingness-to-pay programs were found to be influenced by the participant’s age, income, educational level, occupation, level of information about the local environmental situation, and (as environmental restoration can require long-time frames to achieve goals) the number of children under the age of 15 in the household (Ojeda, 2008).

Lack of trust between major water users (e.g., municipalities, agriculture, mining, industry) and proponents of environmental flows can also limit stakeholder participation. Information on how specific environmental flows programs will impact sectors can help improve project participation. In all cases, with increased knowledge and awareness of how water resource decisions affect lives and livelihoods, community interest, empowerment, and engagement can all be increased.

SECTION III – TECHNIQUES AND CHALLENGES TO PREDICTING FLOWS

As many water conservation objectives are not maintained, it is important to know how to ensure plans for environmental flows will be successful under long-term planning scenarios. In the arid regions of the desert Southwestern United States and Northern Mexico it can be critical for all involved parties to have discussions and come to agreements on what is the correct path forward. Often geopolitical or organizational borders can hinder the ability to implement the basin-scale water management policy necessary to address issues commonly encountered in water-stressed areas. This section covers strategies and challenges in predicting future flows and techniques for achieving desired outcomes.

Key Questions for Section III:

- What are techniques to predict when pulse flows are available and how is information communicated among parties to provide flows?
- Are there examples where reservoir release schedules incorporated environmental flows? How were these schedules created?
- How do groundwater flow models predict ranges in variability of base flow associated with climate change and aquifer management?
- How have projects incorporated flexibility or adaptive management into their environmental flow prescriptions?
- What role do existing regulations or policies play in the ability to predict and provide environmental flows?
- What role do international agreements or partnerships have in successfully predicting and managing environmental flows?

WHAT ARE TECHNIQUES TO PREDICT WHEN PULSE FLOWS ARE AVAILABLE AND HOW IS THIS INFORMATION COMMUNICATED AMONG PARTIES TO PROVIDE FLOWS?

Due to the control of surface flows in desert rivers, timing and volume of pulse flow events can be limited when compared to historic conditions. These circumstances, however, allow human-induced high flow pulses to be utilized to mimic natural system behavior. There are two options for determining when pulse flows are available: (1) predictions associated with a precipitation event or (2) use of existing water supplies. Predicting storm timing and intensity and which bodies of water or reservoirs will be filled can be difficult. Given this consideration, the option of using existing water supplies can often produce more reliable results.



FIGURE 12 - NEAR PEAK FLOW EVENT OF AN EPHEMERAL STREAM IN NEW MEXICO.
(PHOTO CREDIT: USGS, 2005)

To conduct experimental releases, it is first recommended to produce environmental flow hydrographs focused on achieving explicit ecological targets in reaches downstream of reservoirs. Produced hydrographs should contain information associated with achieving target flow characteristics, including depth, duration, timing, and rate of change (Wang, 2013).

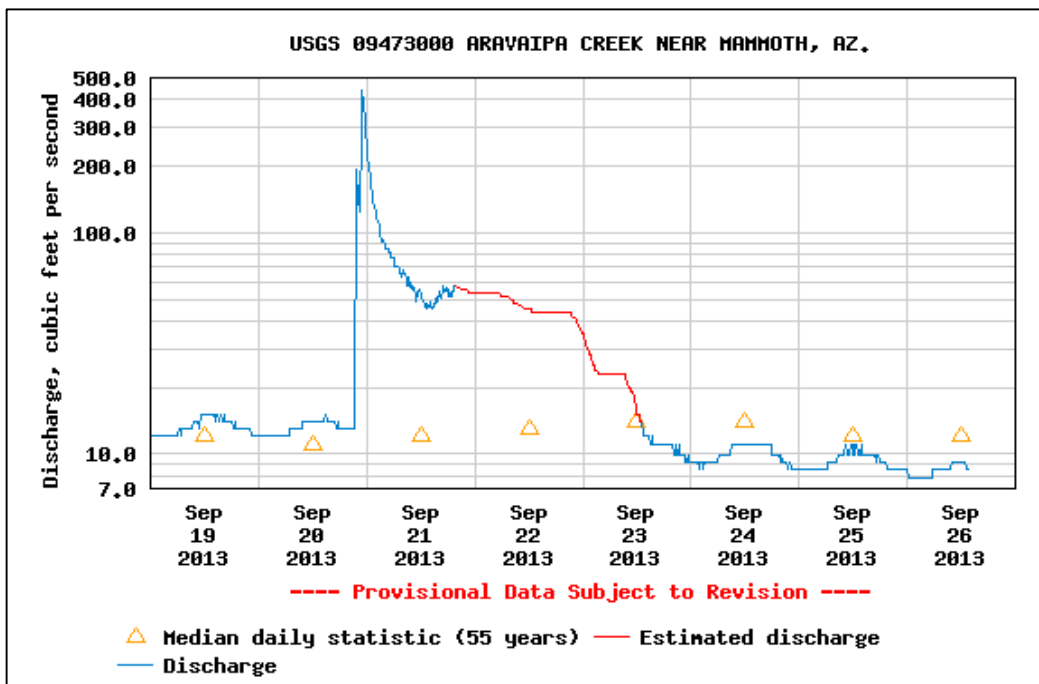


FIGURE 13 - SEVEN DAY HYDROGRAPH FROM USGS STREAM GAGE NEAR MAMMOTH, ARIZONA. INTENSITY AND TIMING OF PEAK FLOW EVENTS CAN BE DIFFICULT BUT IMPORTANT TO PREDICT. (SOURCE: USGS, 2013)

ARE THERE EXAMPLES WHERE RESERVOIR RELEASE SCHEDULES INCORPORATED ENVIRONMENTAL FLOWS? HOW WERE THESE SCHEDULES CREATED?

While not extremely common, examples of reservoir release schedules incorporating considerations for environmental flows are included in Table 3.

TABLE 3 - CASES WHERE RESERVOIR RELEASE SCHEDULES INCORPORATED ENVIRONMENTAL FLOWS

System	Information	Reference
Colorado River, Arizona	High flow experiments were conducted downstream of the Glen Canyon Dam to rehabilitate sand bars and beaches along the Colorado River. This was completed as part of an adaptive management program, which allowed changes in dam operations to release high pulses of water. Preliminary decisions on how to conduct flow releases were determined by multi-stakeholder adaptive management groups, the Bureau of Reclamation, and the USGS utilizing sediment modeling software. To conduct pulse flow experiments and create environmental flow recommendations in the Grand Canyon, a budget of ~\$11 million dollars a year, for ~15 years, was needed.	Glen Canyon Dam Long-Term Experimental and Management Plan Environmental Impact Statement, USDOJ, 2016
Colorado River Delta, U.S. and Mexico	In 2014 releases to Mexico were modified to provide water through pulse events for environmental flows to the Colorado River Delta. Requiring one year of planning to accomplish, the March 2014 release implemented under a U.S. – Mexico agreement, “Minute 319”, sent 105,000 acre-feet of flow south from Morelos Dam. Using Landsat 8 satellite imagery, researchers calculated from August 2013 (pre-flow) to August 2014 (post-flow) a 43% increase in green vegetation in areas wetted by the flow and a 23% increase in greening of the riparian zone.	NASA, 2014; Environmental Defense Fund, 2014
Bill Williams River, Arizona	Experimental pulse flow releases were conducted from a large reservoir to illustrate how geomorphic processes can influence planning and objective setting for an environmental flow program. The Alamo Dam release schedule, developed in 1992, involves seasonal release and reservoir elevation standards with an inherent recognition of climate conditions. Using a reservoir operations model, a range of scenarios were simulated for reservoir release volume, water level, and resultant impacts to downstream flows. The model was run in conjunction with one and two-dimensional hydraulics models to predict stage-discharge relationships at point and river scale. In addition, a groundwater model was run to determine surface-groundwater interactions in an alluvial valley in the basin.	U.S. Army Corps of Engineers Water Control Manual for Alamo Dam, 2003; Shafroth et al., 2010
Middle Rio Grande, New Mexico	Flow releases from the Abiquiu Reservoir on the Rio Chama were conducted to simulate spring pulse flushes for ecological purposes (e.g., endangered Rio Grande silvery minnow). Pulse volumes were	Magaña, 2012; USBR, 2014

	based on the requirement to flood newly re-created backwater channels in the bosque areas. By altering typical dam release timing and volume, environmental flow goals were achieved to provide water to sensitive habitat niches along the river edge.	
Trinity River, California	In accordance with US DOI mandates, flows were increased from 10-30% of historical rates to greater than 50% to improve salmon habitat. In 2011, the largest authorized release of water for restoration purposes was conducted from the Trinity Dam at 11,000 cfs.	Trinity River Restoration Program, 2016
Savannah River, South Carolina and Georgia	Flow recommendations were produced for dry, average, and wet years in three reaches of the river. Over a 3-day ecosystem flow workshop, a range of flow recommendations for monthly low flows, yearly pulse flows, and floods with targeted inter-annual frequencies were generated. In collaboration with The Nature Conservancy, values were incorporated into a river basin planning effort by the U.S. Army Corps of Engineers.	Richter, 2006
Yangtze River, China	Downstream from the Three Gorges Reservoir, hydrographs were produced to illustrate ecological conservation targets and associated time schedules to achieve goals.	Wang et al., 2013
Huai River, China	Utilization of the AEHRA method downstream of a series of dams determined ecological impacts of alternative release schedules. This approach was found to be well-suited to predicting seasonal variation of instream flows for rivers with limited ecological and hydrological data.	Liu et al., 2010



FIGURE 14 - GLEN CANYON DAM ON THE COLORADO RIVER, ARIZONA (PHOTO CREDIT: WIKIMEDIA COMMONS)

HOW DO GROUNDWATER FLOW MODELS PREDICT RANGES IN VARIABILITY OF BASE FLOW ASSOCIATED WITH CLIMATE CHANGE AND AQUIFER MANAGEMENT?

Many predictive groundwater models were developed for the purpose of measuring aquifer levels under different rates of removal or replenishment. It is important to consider software and geography-specific considerations when applying and interpreting results.

A thorough understanding of the strength of surface water-groundwater interconnectivity can provide valuable information on how climate shifts and alternative development and pumping scenarios may alter surface water flows throughout the year. Given uncertainties, model resolution should be selected to capture major system heterogeneity. Linking this information to biological thresholds provides insights into how much groundwater should be present to promote growth and proliferation of desirable riparian species.

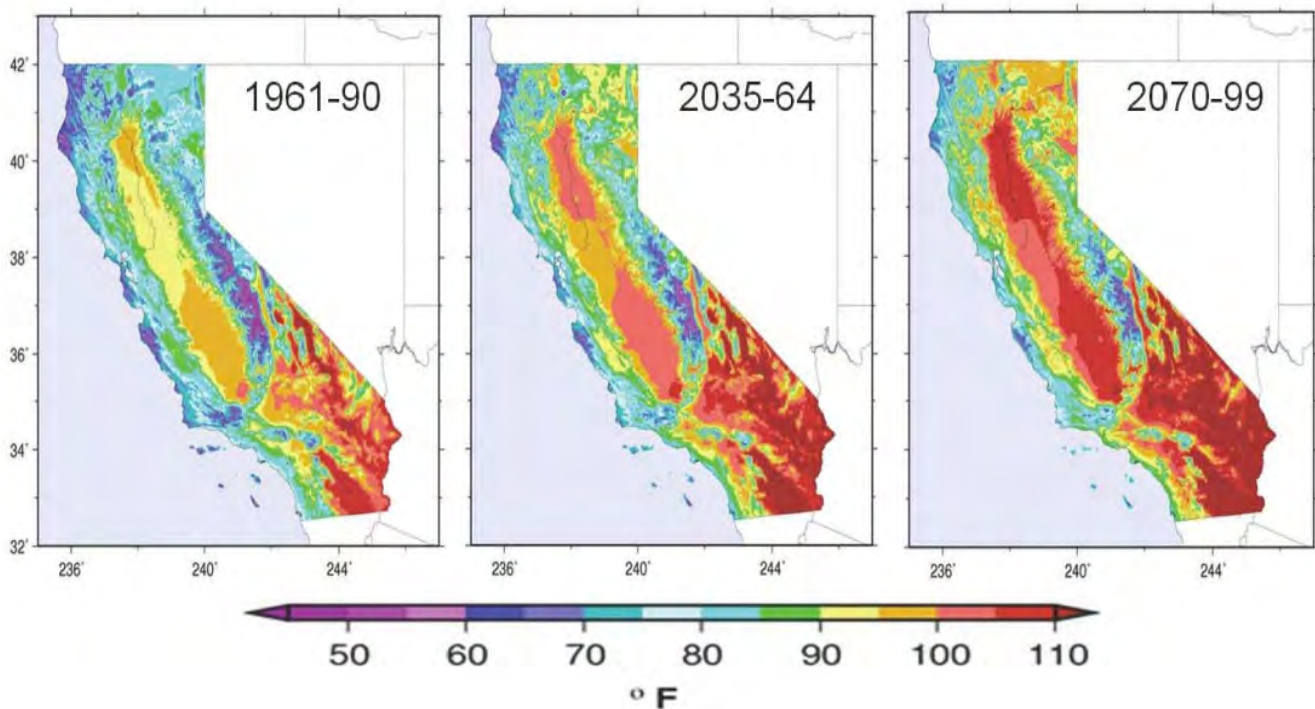


FIGURE 15 - CALIFORNIA HISTORICAL AND PROJECTED JULY TEMPERATURE INCREASE (1961-2099). SHIFTS IN TEMPERATURE WILL IMPACT PRECIPITATION TIMING AND AMOUNT, EVAPOTRANSPIRATION RATES, AND ULTIMATELY, BASE-FLOW CONDITIONS OF RIPARIAN SYSTEMS. (SOURCE: CAYAN, 2009 FROM CALIFORNIA NATURAL RESOURCES AGENCY, 2009)

In one example, MODFLOW modeling software was used to simulate surface water and groundwater interactions in an alluvial valley in the Bill Williams River with infrequent flows. This groundwater budget ultimately provided estimates of surface flow downstream of the valley, sub-surface flow downstream of the valley, and evapo-transpirative losses from the basin (Shafroth et al., 2010). Using MODFLOW to determine surface water-groundwater interactions is

an approach which is commonly used by the USGS and has also been applied to predict groundwater pumping impacts to San Pedro River flows in Arizona.

HOW HAVE PROJECTS INCORPORATED FLEXIBILITY OR ADAPTIVE MANAGEMENT INTO ENVIRONMENTAL FLOWS?

While it can be a great accomplishment to get an environmental flow program established, achieving long-term project objectives can be difficult or impossible if evolution and flexibility of the process is not considered. The adaptive management process can be especially effective when multiple stakeholder groups are able to come together to agree on next steps when faced with new information and changing land and water resource conditions (Acreman and Dunbar, 2004; King, 2003). Communication among parties with different priorities can generate a relationship of trust between stakeholders and agencies. Water managers can help scientists better understand how to prescribe flow targets in a manner that is achievable, and scientists can help water managers learn about ecological effects of alternative management plans. Water managers can also benefit from increased knowledge of the uncertainties involved in the techniques and analyses conducted to determine flow targets. This exchange of information can help key players and the general public feel as though their needs are being considered in the decision-making process and lead to increased acceptance of further experimentation and adaptive management planning (Richter et al., 2003).



FIGURE 16 - LOWER COLORADO RIVERBED BEFORE AND DURING THE MARCH 2014 PULSE FLOW. WHILE MOST OF THE WATER SEEPED INTO THE GROUND IN THE FIRST 37 MILES BELOW MORELOS DAM, THE FLOW REACHED THE SEA OF CORTEZ FOR THE FIRST TIME SINCE 2000. (PHOTO CREDIT: NASA, 2014)

In examples including the Colorado River in the Grand Canyon, the Colorado River Delta, and the Bill Williams River in Arizona, adaptive management was incorporated into project designs and is ongoing. On the Bill Williams River, findings from model runs and experimental flow releases are contributing to adaptive flow management and the development of regional environmental flow standards (Shafroth et al., 2010). Longitudinal complexity and ecohydrological feedbacks

were key informational factors used to adapt plans. Specifically, the focus was on achieving geomorphic thresholds and adding to knowledge on the ecosystem effects of spatial and temporal variations in flow.

While adaptive management has been identified as critical to long-term success of some projects, it has not been broadly applied for environmental flow restoration efforts. To rectify this situation, Richter (2006) proposed a flexible, five step approach to fit any organization's available resources:

1. Orientation meeting with local, state, and federal agencies, academics, scientists, and water managers;
2. Literature review and summary of existing knowledge on flow-dependent species and ecological processes of concern;
3. Workshop to develop ecological and flow objectives and identify key information gaps;
4. Trial basis implementation of flow recommendations, to test hypotheses and reduce uncertainties;
5. System response monitoring and further research to address key issues. These findings can be used to encourage deliberate learning and provide the information necessary for adapting the flow management plan over time.

Additional information on techniques that incorporate adaptive management into protocols (e.g., DRIFT, IHA) can be found in the [Appendix](#).

WHAT ROLE DO EXISTING REGULATIONS OR POLICIES PLAY IN THE ABILITY TO PREDICT AND PROVIDE FLOWS?

As water rights for environmental flows are not universal (Loehman and Charney, 2011) and established water users are often not required to consider their impact on the environment (Megdal, Nadeau, and Tom, 2011), it can be difficult to include the needs of riparian and aquatic ecosystems when other existing uses already outstrip supplies (Hirji and Davis, 2009). Therefore, regulations and policies that can directly and indirectly influence water rights, costs, uses, and possible approaches for environmental flow implementation are critical to predicting and providing flows. Some policies can specifically stipulate the need to provide water for environmental flows and address the need to collect vital information, while other mandates may prioritize out-of-stream demands in the face of increased growth and development. In Texas, for example, policies are not designed to provide or measure flows to achieve ecological targets, but for the purpose of knowing the maximum amount of water available for extraction. In other regions, the problem may not be an absence of protective measures, but rather the nonsystematic way in which institutional mechanisms are applied (Lamb, 1995).

New policies may gain greater acceptance when watershed management is integrated into greater land management practices in the region. Other factors in acceptance include: how the policy will affect the needs of a wide range of stakeholders; how it fits into current and future policies; and how it agrees with scientific evidence (Macleod, 2007).

Policies that influence data availability or usability can also limit the ability to predict and provide environmental flows. This is the case for CONAGUA in Mexico, which relies solely on their official meteorological stations to conduct studies that influence future water resource management policies. Incorporation of additional data sources could help provide a more holistic understanding of how decisions can impact flows.

The Alberta Water Act (2000) from Canada is a good example of legislation that includes reference to a “water conservation objective.” It explicitly incorporates (1) protection of a natural water body or its aquatic environment, or any part of it; (2) protection of tourism, recreational, transportation, or waste assimilation uses of water, and; (3) management of fish or wildlife. It also includes requirements for water necessary to achieve a specified rate of flow or water level.

WHAT ROLE DO INTERNATIONAL AGREEMENTS OR PARTNERSHIPS HAVE IN SUCCESSFULLY PREDICTING AND MANAGING ENVIRONMENTAL FLOWS?

In transboundary river basins, numerous parties can be interested in utilizing the resource, often with their own discrepant goals, objectives, and valuation of natural river function. International agreements and partnerships can play a fundamental role in reconciling divergent interests toward achieving environmental flow goals.

International laws and other instruments include: treaties, rights and duties of states in international river basins, and non-binding instruments (e.g., soft laws such as codes of conduct, guidelines, principles, or recommendations). Some agreements focus on watercourses where applicable international water laws can influence environmental flows, while others establish more specific provisions for how flows should be regulated.

Hesitancy to develop international water management plans can be associated with current and future limitations on water resource availability and/or a lack of trust between controlling parties. Goodwill among parties needs to be established and can begin with something as simple as an agreement to share information between agencies, states, or educational institutions. Once basic understanding and information sharing begins, it can open the door to further discussions related to obligations associated with water treaties and ways in which they can be modified to improve environmental system function.

Successes have been identified around the world. Minute 319 (2012) to the 1944 Colorado River treaty between the United States and Mexico represents a historic example of international collaboration that achieved environmental flow goals. Partnerships between Pro-Natura, the Sonoran Institute, and other government and non-governmental organizations were essential to bringing about this agreement.



FIGURE 17 - FORMER U.S. DEPARTMENT OF INTERIOR SECRETARY SALAZAR JOINS U.S. AND MEXICO DELEGATIONS FOR HISTORIC COLORADO RIVER WATER AGREEMENT IN 2012. (PHOTO CREDIT: US DOI)

While not specific to environmental flows, another example of binational agreement and success for improved water resource management was on the Rio Grande between the United States and Mexico. In this program, local Mexican nationals from the village of Boquillas (administered by the Comisión Nacional de Áreas Naturales Protegidas (CONANP)) and the Big Bend National Park staff reached a mutually beneficial agreement to work together and more effectively control fire events and invasive species outbreaks along the river's edge (Sirotnak, 2011).

In an International Union for Conservation of Nature (IUCN) report, Dyson (2003) provides further information on several international treaties that address conservation and sustainable use of river basins as part of a wider watershed approach. The report answers questions related to funding, training methods, raising awareness and understanding, and gaining commitment from the community and political leaders.

CONCLUSIONS

The collection of high-quality data and its incorporation into desert environmental flow programs and policies is critical to the long-term maintenance of these sensitive ecosystems. To help establish and protect such programs, this document provides information on how to determine reasonable and achievable flow goals to meet ecological objectives, the limitations of various approaches, and how organizations in arid regions around the world have addressed problems encountered along the way to developing and maintaining environmental flows programs. Insights are provided into what public and private players need to be involved in the process, and how best to explain environmental flows concepts in a way that promotes long-term planning and ensures goals will be met into the extended future.

Given arid landscape water supply limitations, collaborative planning with all major stakeholders is critical to protecting and maintaining the riparian resources that can influence long-term ecologic and socio-economic viability of a region. Through integrated water resource management approaches that take into account meeting the reasonable needs of water users while safeguarding the environment, the interests of environmental organizations, governments, and local stakeholders can all be met. Through this participatory and democratic process, resource management can be achieved in a manner that is more comprehensive and inclusive than is traditionally conducted using isolated sectoral approaches. Ignoring the need for these partnerships can lead to the perpetuation of practices that further degrade social and natural systems, ultimately resulting in all parties being dissatisfied with the outcomes.

As significant hydrologic and ecologic change continues to occur in arid landscapes and elsewhere around the world, advances in the sciences that contribute to understanding riparian system interconnectivity and healthy function are imperative. Further study of long-term monitoring sites, pulse flow experiments, and the response of socio-economic and ecological systems to changes in river flows will support new environmental flows programs. Such programs can be implemented with greater frequency, improved cost effectiveness, and more regularly attain objectives related to restoring natural system function for the benefit of aquatic and terrestrial species.

REFERENCES

- Acreman, M. C. and Dunbar, M. J. (2004). Defining environmental river flow requirements? a review. *Hydrology and Earth System Sciences Discussions*, 8(5), 861-876.
- Acreman, M. (2005). Linking science and decision-making: features and experience from environmental river flow setting. *Environmental Modelling & Software*, 20, 99–109.
- Alcazar, J., and Antoni, P. (2010). Establishing environmental flow regimes in a Mediterranean watershed based on a regional classification. *Journal of Hydrology*, 388, 41–51.
- Arthington, A. H., Bunn, S. E., Poff, N. L., and Naiman, R. J. (2006). The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications*, 16(4), 1311-1318.
- Arthington, A. H. and Zalucki, J. M. (1998). Comparative evaluation of environmental flow assessment and techniques: review of methods. *Land and Water Resources Research and Development Corporation*.
- Barry, T. (2015). Water wars: water crisis destabilizing northern Mexico as the Yaqui lose major water battle in Sonora. Center for International Policy, Washington, D.C.
- Belmar, O., Velasco, J., and Martinez-Capel, F. (2011). Hydrological classification of natural flow regimes to support environmental flow assessments in intensively regulated Mediterranean rivers, Segura River Basin (Spain). *Environmental Management*, 47, 992–1004.
- California Natural Resources Agency. (2009). California climate adaptation strategy: a report to the governor of the State of California in response to Executive Order S-13-2008.
- Cayan, D., Tyree, M., Dettinger, M., et al. (2009). Climate change scenarios and sea level rise estimates for the California 2008 climate change scenarios assessment. PIER Research Report, CEC- 500-2009-014, Sacramento, CA: California Energy Commission.
- Center for the Future of Arizona. (2009). The Arizona we want (p. 40). Phoenix, Arizona: Center for the Future of Arizona.
- Colman, Zack. (March 8, 2017). How water swaps help the West manage a precious resource. The Christian Science Monitor. <http://www.csmonitor.com/Environment/Inhabit/2017/0308/How-water-swaps-help-the-West-manage-a-precious-resource>
- Colorado Parks and Wildlife Commission. (2014). Rio Grande cooperative project: overview and Colorado Parks and Wildlife role.
- Douglas, A. J. (2009). Social, political, and institutional setting: water management problems of the Rio Grande. *Journal of Water Resources Planning and Management*, 135, 493–501.
- Dyson, M., Bergkamp, G., and Scanlon, J. (2003). Flow - the essentials of environmental flows - water and nature initiative. IUCN, 2nd edition.
- Environmental Defense Fund. (2014). Bringing the river back to the sea. <http://www.edf.org/sites/default/files/pulseflow/index.html>
- Everard, M. (2004). Investing in sustainable catchments. *Science of the Total Environment*, 324(1), 1-24.

- Fernandez-Gimenez, M. E., Ballard, H. L., and Sturtevant, V. E. (2008). Adaptive management and social learning in collaborative and community-based monitoring: a study of five community-based forestry organizations in the western USA. *Ecology and Society*, 13(2).
- Gippel, C. J., and Stewardson, M. J. (1998). Use of wetted perimeter in defining minimum environmental flows. *Regulated Rivers: Research and Management*, 14(1), 53–67.
- Gómez-Balandra, M. A., del Pilar Saldaña-Fabela, M., and Martínez-Jiménez, M. (2014). The Mexican environmental flow standard: scope, application and implementation. *Journal of Environmental Protection*, 5(1), 71.
- Grayson, R., and Blöschl, G. (2001). Spatial patterns in catchment hydrology: observations and modelling. CUP Archive.
- Hirji, R., and Davis, R. (2009). Environmental flows in water resources policies, plans, and projects: findings and recommendations. World Bank Publications.
- Hughes, D. A., and Pauline, H. (2003). A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. *Journal of Hydrology*, 270(3), 167-181.
- IUCN The World Conservation Union. (2000). Vision for water and nature: a world strategy for conservation and sustainable management of water resources in the 21st Century. <http://www.rivernet.org/general/docs/VisionWaterNature.pdf#page=27&zoom=auto,-209,799>
- Jowett, I. G. (1997). Instream flow methods: a comparison of approaches. *Regulated Rivers-Research and Management*, 13, 115–127.
- Jowett, I. G., & Richardson, J. (1995). Habitat preferences of common, riverine New Zealand native fishes and implications for flow management. *New Zealand Journal of Marine and Freshwater Research*, 29(1), 13-23.
- Karim, K., Gubbels, M. E., and Goulter, I. C. (1995). Review of determination of instream flow requirements with special application to Australia. *Journal of the American Water Resources Association*, 31(6), 1063–1077.
- Katz, D. (2006). *Going with the flow: preserving and restoring instream water allocations*. Washington, DC: Island Press.
- Kendy, E., Apse, C., and Blann, K. (2012). A practical guide to environmental flows for policy and planning. *The Nature Conservancy*.
- King, J., Brown, C., and Sabet, H. (2003). A scenario based holistic approach to environmental flow assessments for rivers. *River Research and Applications*, 19, 619-639.
- Lamb, B. L. (1995). Criteria for evaluating state instream-flow programs: deciding what works. *Journal of Water Resources Planning and Management*, 121(3), 270–274.
- Lebel, L., Garden, P., and Imamura, M. (2005). The politics of scale, position, and place in the governance of water resources in the Mekong region. *Ecology and Society*, 10(2), 18.
- Le Quesne, T., Kendy, E., and Weston, D. (2010). The implementation challenge: taking stock of government policies to protect and restore environmental flows. World Wildlife Fund, The Nature Conservancy.

- Loehman, E. T., and Charney, S. (2011). Further down the road to sustainable environmental flows: funding, management activities and governance for six western US states. *Water International*, 36, 873–893.
- Macleod, C. J. A., Scholefield, D., and Haygarth, P. M. (2007). Integration for sustainable catchment management. *Science of The Total Environment*, 373(2), 591-602.
- Magaña, H. (2012). Habitat use of the Rio Grande silvery minnow (*Hybognathus amarus*) during a long-term flood pulse in the Middle Rio Grande, New Mexico. *Environ Biol Fish*, 95, 201–212.
- Matthews, R. and Richter, B. D. (2007). Application of the indicators of hydrologic alteration software in environmental flow setting. *Journal of the American Water Resources Association*, 43(6), 1400-1413.
- Megdal, S. B., Nadeau, J. B., and Tom, T. (2011). The forgotten sector: Arizona water law and the environment. *Arizona Journal of Environmental Law and Policy*, 1, 243-243.
- Montana Department of Natural Resources. (2014). Yellowstone River Basin Water Plan. http://dnrc.mt.gov/divisions/water/management/docs/state-water-plan/yellowstone/river-basin-plan/yellowstone_river_basin_report_final.pdf
- Mott Lacroix, K., Tapia, E., and Springer, A. (2016). Desert LCC environmental flows database and desert flows assessment: environmental water needs of riparian and aquatic ecosystems in the desert watersheds of the U.S. and Mexico. University of Arizona Water Resources Research Center. <https://www.sciencebase.gov/catalog/item/5494ce05e4b0a2b9adad8efc>
<https://wrrc.arizona.edu/desertflowsdata>
- Mott Lacroix, K., Tapia, E., and Springer, A. (2017). Environmental flows in the desert rivers of the United States and Mexico: synthesis of available data and gap analysis. *Journal of Arid Environments*, 140, 67-78.
- Muro, M. and Jeffrey, P. (2008). A critical review of the theory and application of social learning in participatory natural resource management processes. *Journal of Environmental Planning and Management*, 51(3), 325-344.
- Nadeau, J., and Megdal, S. (2012). Arizona environmental water needs methodology guidebook. University of Arizona Water Resources Research Center. [https://wrrc.arizona.edu/sites/wrrc.arizona.edu/files/Guidebook PDF_1.pdf](https://wrrc.arizona.edu/sites/wrrc.arizona.edu/files/Guidebook%20PDF_1.pdf)
- NASA. (2014). NASA/USGS satellite sees green-up along Colorado River’s delta after experimental flow. <https://www.nasa.gov/content/goddard/nasa-usgs-satellite-sees-green-up-along-colorado-rivers-delta-after-experimental-flow>
- OIA (Outdoor Industry Association). (2012). The outdoor recreation economy. <https://outdoorindustry.org/recreationeconomy>
- Ojeda, M. I., Mayer, A. S., and Solomon, B. D. (2008). Economic valuation of environmental services sustained by water flows in the Yaqui River Delta. *Ecological Economics*, 65(1), 155-166.
- Pahl-Wostl, C. (2006). The importance of social learning in restoring the multifunctionality of rivers and floodplains. *Ecology and Society*, 11(1).

- Poff, N. L., and Zimmerman, J. K. H. (2010). Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, 55(1), 194–205.
- Poff, N. L., Allan, J. D., Palmer, M. A., Hart, D. D., Richter, B. D., Arthington, A. H., ... Stanford, J. A. (2003). River flows and water wars: emerging science for environmental decision making. *Frontiers in Ecology and the Environment*, 1(6), 298–306.
- Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., et al. (1997). The natural flow regime: a paradigm for river conservation and restoration. *Bioscience*, 47(11), 769-784.
- Reed, M., et al. (2010). What is social learning? *Ecology and Society*, 15(4), r1.
- Richter, B. D., Warner, A. T. Meyer, J. L., and Lutz, K. (2006). A collaborative and adaptive process for developing environmental flow requirements. *River Research and Applications*, 22(3), 297-318.
- Richter, B. D., Matthews, R., Harrison, D. L., and Wigington, R. (2003). Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications*, 13(1), 206-224.
- Richter, B., Baumgartner, J., Wigington, R., and Braun, D. (1997). How much water does a river need? *Freshwater Biology*, 37(1), 231–49.
- Rio Grande Basin Roundtable. (2015). Rio Grande Basin Implementation Plan – Executive Summary. <https://www.colorado.gov/pacific/sites/default/files/rgbip-es-final.pdf>
- Roach, K. A. (2013). Texas water wars: how politics and scientific uncertainty influence environmental flow decision-making in the Lone Star state. *Biodiversity and Conservation*, 22 (3), 545–565.
- Rodríguez-Pineda, J. A. (2013). Determinación de caudales ecológicos en la Cuenca del río Conchos. Unpublished World Wildlife Fund (WWF) report de la Oficina en Chihuahua, Programa Desierto Chihuahuense.
- Shafroth, P. B., Wilcox, A. C., Lytle, D. A., Hickey, J. T., Andersen, D. C., Beauchamp, V. B., Hautzinger, A., McMullen L. E., and Warner, A. (2010). Ecosystem effects of environmental flows: modeling and experimental floods in a dryland river. *Freshwater Biology*, 55(1), 68-85.
- Sirotnak, J. (2011). Cooperation in the Big Bend Region. Fulfilling the international mission of the National Park Service. *The George Wright Forum*, 28(3), 291-295.
- Smakhtin, V. U., Shilpakar, R. L., and Hughes, D. A. (2006). Hydrology-based assessment of environmental flows: an example from Nepal. *Hydrological Sciences Journal*, 51(2), 207-222.
- State of Washington Department of Ecology. (2017). Water resources: water market. <http://www.ecy.wa.gov/programs/wr/market/market.html>
- Stewardson, M. J., and Gippel, C. J. (2003). Incorporating flow variability into environmental flow regimes using the flow events method. *River Research and Applications*, 19(5–6), 459–472.
- Swales, S., & Harris, J. H. (1995). The expert panel assessment method (EPAM): a new tool for determining environmental flows in regulated rivers. *The Ecological Basis for River Management*, 125-134.

- Tarlock, A. D. (2014). Mexico and the United States assume a legal duty to provide Colorado River delta restoration flows: an important international environmental and water law precedent. *Review of European, Comparative & International Environmental Law*, 23(1), 76-87.
- Tharme, R. E., and King, J. M. (1998). Development of the Building Block Methodology for instream flow assessments, and supporting research on the effects of different magnitude flows on riverine ecosystems. Water Research Commission.
- Tharme, R. E. and King, J. M. (2008). Environmental flow assessments for rivers: manual for the Building Block Methodology. *Water Research Commission*, TT 354/08.
- Trinity River Restoration Program. (2016). <http://www.trrp.net/restore/flows>
- Wang, J., Dong, Z., Li C., Feng, S., Luo, H., and Peng, Q. (2013). An environmental flow assessment method based on the relationships between flow and ecological response: a case study of the Three Gorges Reservoir and its downstream reach. *Science China Technological Sciences*, 56(6), 1471-1484.
- USBR. (2011). Yakima River basin study: market-based reallocation of water resources. U.S. Bureau of Reclamation Technical Memorandum. <https://www.usbr.gov/pn/programs/yrbwep/reports/tm/4-12marketreallocation.pdf>
- USBR. (2012). Yakima River basin integrated water resource management plan: four accounts analysis of the integrated plan. <https://www.usbr.gov/pn/programs/yrbwep/reports/fouraccounts.pdf>
- USBR. (May 5, 2014). Water managers cooperate to create beneficial river flows. U.S. Bureau of Reclamation News Release Archive. <https://www.usbr.gov/newsroom/newsrelease/detail.cfm?RecordID=46764>
- USBR. (2017). Moving forward effort: Colorado basin stakeholders moving forward to address challenges identified in the Colorado River basin water supply and demand study. <https://www.usbr.gov/lc/region/programs/crbstudy/MovingForward/>
- USDOI (Department of Interior). (2016). Glen Canyon Dam Long-Term Experimental and Management Plan EIS. <http://ltempeis.anl.gov/>
- USGS. (2005). Automated crest-stage gage application in ephemeral streams in New Mexico. U.S. Geological Survey Fact Sheet 2005-3136.
- USGS. (2014). First USGS streamgage records 125 years of measuring New Mexico's vital water resources. www.usgs.gov/news/first-usgs-streamgage-records-125-years-measuring-New-Mexico's-vital-water-resources
- Yin, X. A., and Yang, Z. F. (2011). Development of a coupled reservoir operation and water diversion model: balancing human and environmental flow requirements. *Ecological Modelling*, 222(2), 224-231.

APPENDIX:

ADDITIONAL INFORMATION ON METHODS USED TO DETERMINE FLOWS

This appendix provides additional information on the methods listed in [Table 1 \(Section I\)](#). The methods are listed according to the four method types: (I) *look-up tables*, (II) *desktop analysis*, (III) *habitat modeling*, and (IV) *holistic analysis*. Depending on geographic circumstances certain methods will be more appropriate than others. For additional information on specific methods, review the [Arizona Water Needs Methodology Guidebook](#) (Nadeau, 2012). To conduct a specialized database search focused on a particular method, riparian system type (e.g., ephemeral, intermittent, perennial), or geographic region, refer to the DLCC-funded [Desert Flows Database](#) (Mott Lacroix, 2016).

I. LOOK-UP TABLE METHODS

FLOW DURATION CURVE: With historical flow data a monthly flow duration curve can be produced, providing cumulative return periods for given flows. Based on 20 years of daily flow measurements, this method makes a monthly median flow recommendation as established by the developers of this method, the Northern Great Plains Resource Program. To avoid abnormal events, it is recommended to set the instream flow protection at the 90th percentile for average flows, and the 50th percentile for higher, wet season flows (Karim et al., 1995).

HYDROLOGICAL INDEX: According to the French Freshwater Fishing Law of 1984, bypassed sections of rivers must have remaining flows with a lower limit of $1/40^{\text{th}}$ of the average flow for existing schemes and $1/10^{\text{th}}$ for new schemes (Karim et al., 1995).

NATURAL FLOW INDEX: Using hydrological data, in the United Kingdom, the Q95 determination is often used, where the flow target is equaled or exceeded 95% of the time. Similar examples of this method include 7Q10 (Kendy, 2012) and Q347 (Alcazar, 2010) which consider the number of days annually that a flow goal is met or exceeded.

TENNANT METHOD: This method develops a correlation between habitat quality and percentages of Mean Annual Flow (MAF). Quality of habitat, as measured by dry and wet periods also called "Base Flow Regimens", varies from severely degraded (10% of MAF) to barely sufficient for short-term survival during flushing flows (200% of MAF) (Karim et al., 1995). It requires limited additional data collection, and the desktop analysis is site-specific (Dyson and Scanlon, 2003). About two to four months of data are required to complete a study (Hirji and Davis, 2009).

II. DESKTOP ANALYSIS METHODS

WETTED PERIMETER: This method is based on an analysis of wetted perimeter variations of a single cross-section. It is commonly used across riffles, which tend to have productive benthic habitats. For fish spawning or maximum production of benthic invertebrates, minimum flows are identified from a discharge near the breakpoint of the wetted perimeter discharge curve (Tharme and King, 1998).

The wetted perimeter method can be used in cases of scarce information availability. With moderate to low data requirements, this method can be accomplished in one to two months (Hirji and Davis, 2009).

RICHTER METHOD: The primary goal of this method is the protection of the natural ecosystem (Dyson and Scanlon, 2003). For every indexed magnitude of flow regime, from low to high, the components of natural flow are identified (e.g., timing, frequency and duration of flows). A gaged daily flow set is used with 32 indices.

DAILY WATER ACCOUNTING: This method is a risk-mapping tool for water use planning (Kendy, 2012).

STREAMFLOW DEPLETION MODEL (STRMDPL): This method estimates groundwater pumping delay and can be used as an online tool for estimating impacts of proposed water withdrawals (Kendy, 2012).

SUSTAINABLE YIELD ESTIMATOR (SYE): Utilizing a “duration curve regression model with water accounting”, this method can determine environmental flow criteria for permitting existing and future water withdrawals (Kendy, 2012). It has been used to determine statewide reservoir release rules based on the needs of river species by bioperiod. Specific flow needs are determined by technical committee recommendation.

LOTIC INVERTEBRATE INDEX FOR FLOW EVALUATION (LIFE): This method is performed through the collection of routine macro-invertebrate monitoring data. It can take up to five years and be costly to complete due to the time and hydraulic and ecological data requirements (Dyson and Scanlon, 2003; Hirji and Davis, 2009).

III. HABITAT MODELING METHODS

RANGE OF VARIABILITY APPROACH (RVA): Initial streamflow-based river management targets can be defined using this method. Water managers can determine, with limited ecological data, what is the natural range of variation in the system and set preliminary flow targets to maintain ecological integrity. These defined flow prescriptions can then be approved and continually adapted as more ecological and hydrological data become available (Richter, 1997).

In RVA, the role of hydrological variability in maintaining ecosystem function is raised to the highest level. It can be used as a desktop environmental flows assessment tool. It ensures that sufficient water is available for human uses and accepts that the full range of natural streamflow variability will not be possible to maintain in regulated or otherwise affected river systems. This method uses 32 hydrological parameters that reflect different aspects of flow variability, including magnitude, frequency, duration and timing of flows, with the goal of maintaining all parameters within their range of natural variation. A limit of one standard deviation from the mean of each parameter is suggested as a default for setting environmental flow targets (in the absence of other supporting ecological data). Smakhtin (2006) illustrates how techniques, such as RVA, can be modified to simplify the environmental flows assessment process in the absence of local ecohydrological information.

FLOW EVENTS METHOD: Unlike RVA, this method incorporates variability into environmental flows and provides an assessment of flow regimes based on ecosystem function rather than hydrological statistics. Available knowledge is incorporated into the development of flow recommendations and the method accounts for natural dynamism in flow-related ecosystem processes (Stewardson, 2003). The flow events method is conducted in five steps: (1) list ecological factors; (2) define flow events; (3) model hydraulic relations; (4) evaluate flow management scenarios; and (5) specify environmental rules or targets.

To complete the steps, managers can gather information through literature review and expert knowledge. An expert panel can be formed to provide additional information and insights specific to the basin, resulting in improved accuracy and applicability of the method outputs.

When ecological data are limited, researchers can use a theoretical framework to provide guidelines, while acknowledging the uncertainty in assumptions. In addition to providing valuable preliminary information, the theoretical framework can provide justification for further research and follow-up on alternative flow regime impacts.

INSTREAM FLOW INCREMENTAL METHODOLOGY (IFIM): This method, developed by the Cooperative Instream Flow Service Group of the U.S. Fish and Wildlife Service, uses the Physical

Habitat Simulation (PHABSIM) computer package. This software requires temperature and water quality data (Jowett, 1997).

PHYSICAL HABITAT SIMULATION MODEL (PHABSIM): The PHABSIM model is based on the relationship between physical habitat and flow. Through this method, it is possible to transform a flow time series to a habitat time series; generating habitat duration curves that display information related to when target species flow needs will be met (Acreman, 2005).

RIVER HYDRAULICS AND HABITAT SIMULATION PROGRAM (RHYHABSIM): This software is similar to PHABSIM, but with more simplified data requirements (Jowett and Richardson, 1995).

RIVERINE HABITAT SIMULATION PROGRAM (RHABSIM): Developed by Thomas R. Payne & Associates, this program incorporates river hydraulic and aquatic habitat modeling in a Microsoft Windows application (Dunbar et al., 1998; Payne & Associates web site, 2000; cited in Tharme and King, 1998).

COMPUTER AIDED SIMULATION MODEL FOR INSTREAM FLOW REQUIREMENTS (CASIMIR): Used as a habitat simulation method for systems under the influence of hydropower operations, this method is composed of computer models combined to generate relationships of temporal and spatial patterns, such as river bottom stress and flow variation. It can be paired with suitability curves for invertebrate species, using shear stress indices obtained with Statzner hemisphere values. Environmental flow recommendations are based on modelled relationships (Tharme and King, 1998).

RIVER SYSTEM SIMULATOR (RSS): Developed in Norway, this software was designed to address rivers regulated for hydropower. It integrates hydrologic, hydraulic, and habitat simulation models for dynamic habitat modeling over time (Tharme and King, 1998).

RIVERINE COMMUNITY HABITAT ASSESSMENT AND RESTORATION CONCEPT: This method consists of obtaining flow regime information for a location where spatial and velocity conditions are representative of the system prior to impoundment (Nestler et al., 1994, cited in Richter et al., 1997). Informational requirements are moderate to very high and the process can take up to three years to complete (Hirji and Davis, 2009).

COUPLED RESERVOIR OPERATION AND WATER DIVERSION (CROWD) MODEL: The CROWD model can be used to consider reservoir operational needs in tandem with environmental needs (Yin, 2011). This model, applied in the Tang River basin in China, was determined useful for optimizing reservoir operation and water diversion schemes through its analysis of tradeoffs between human and environmental needs. Ultimately this method can help reduce water shortage risks while minimizing ecological disturbance.

IV. HOLISTIC ANALYSIS METHODS

EXPERT PANEL ASSESSMENT METHOD (EPAM): Developed by the New South Wales Departments of Fisheries and Water Resources (Australia), EPAM was the first panel-based approach to environmental flow assessment (Arthington, 1998). Instead of focusing on the health of single components, EPAM is used to monitor river ecosystem health, with survival and conservation of native fish as the main goal. The EPAM is based on ecological interpretation from a panel of local aquatic ecosystem and river management experts; resulting in flow regimes recommendations (Swales and Harris, 1995; Tharme and King, 1998). The effectiveness of this method can be enhanced as additional data become available.

ADAPTED ECOLOGICAL HYDRAULIC RADIUS APPROACH (AEHRA): This method is used to determine instream ecological flows and corresponding seasonal instream ecological water-levels. Liu et al. (2011) describes how this method was applied to a completely dam regulated system to provide predictive capabilities with limited ecological and hydrological data sets (i.e., through the use of generalized geometric channel cross-sectional shapes at un-surveyed sites). Data needs are minimal and the approach yields values necessary for achieving habitat and flow related goals, such as ratio of maximum depth to maximum width of a cross-section and water velocity. Predicted instream environmental flow values using this technique were found to be in fairly good agreement with other commonly used methods (e.g., Tennant, Wetted Perimeter).

BUILDING BLOCK METHODOLOGY (BBM): Developed in South Africa in 1992, BBM relies on available assessment data, model outputs developed by a team of experts, and the application of model outputs to produce a detailed manual for implementation. This method has also been applied in Australia and the United States (Dyson and Scanlon, 2003; Tharme and King, 1998). Review Tharme and King (2008) for additional method details.

HOLISTIC APPROACH: Based on historical flow records, this approach defines natural flow elements to produce a modified regime. It includes percentiles from flow durations, predictability indices, and seasonality of monthly flows. Flow percentiles are often used to define boundary conditions for dry and wet years (Tharme and King, 1998).

HABITAT ANALYSIS AND WATER FLOW RESTORATION METHODOLOGY: Considered a hybrid between the Holistic Approach and BBM, this method focuses on finding a hydrological regime in areas that need to be shifted from a regulated to a pre-regulated state (Tharme and King, 1998).

THE RIVER BABINGLEY METHOD: Based on ecological assessment, this method targets seasonal riparian species survival by assessing trout spawning habitats in autumn or wetlands habitats in spring. The method is based on four general benchmark environmental flows:

"Threshold", "Adequate", "Desirable", and "Optimum." The threshold benchmark is referred to as the flow below which all habitat for a specific species will be lost. This method also incorporates two additional benchmarks for floods: "Channel Maintenance Flow" and "Habitat Maintenance Flow", which take into account geomorphological and sediment flushing processes. The main goal is to build "Ecologically Acceptable Hydrographs", which include provisions for wet and dry conditions, similar to BBM and the Holistic Approach, and produce a Flow Duration Curve representing an "Ecologically Acceptable Flow Regime" (Tharme and King, 1998).

ECOSYSTEMS FUNCTION MODEL: This model is a coupled hydrology-ecology model that links a one-dimensional hydraulic model with the requirements for a desired ecological result, such as riparian tree seedling establishment, native and exotic tree survival, beaver dam integrity, or benthic macroinvertebrate support. Output from this model can be used to produce spatial predictions through a Geographic Information System (GIS) to determine where ecological goals, such as seedling recruitment, can most likely occur. This information, along with location specific output maps, can provide for realistic planning and help focus resources into areas that are most likely to help achieve ecological goals (Tharme and King, 1998).

INDICATORS OF HYDROLOGIC ALTERATION (IHA): Originally developed by the Nature Conservancy in the 1990s, this software accounts for environmental flow components such as low and extremely low flows, pulses, and small and large flood events. The software can also be used to compare pre-impact flow records with post-impact flow conditions to determine which environmental components have been altered and how (Matthews and Richter, 2007). Results can be used to help determine specific alterations and corrections that will improve the success of future flow events at achieving ecological goals.

This method also allows for the differentiation of basins or river systems into distinctive classes based on hydrologic conditions. This classification system can be used to better understand variation along hydrological gradients and help in the development of local and regional environmental flow management strategies.

ECOLOGICAL LIMITS OF HYDROLOGIC ALTERATION (ELOHA) FRAMEWORK: This framework is used for developing regional environmental flow criteria that incorporates hydrological variability. Belmar (2011) conducted work with this framework for the Segura River basin in Spain, incorporating 73 hydrological indices (describing either monthly or annual variation) and 25 years of natural monthly flows (derived from a rainfall-runoff models) to classify river sections based on the similarity in their natural flow regimes. With this technique, major sources of variation can be determined, and the resulting classification can provide a strong basis for the study of the flow alteration-ecological response relationships in each hydrological type.

The indices are based on “Indicators of Hydrologic Alteration” and include data relevant to duration of droughts and dispersion of flow magnitude (average, low, and high flow conditions). Components related to frequency, duration, and rate of change of flood events are not incorporated (Poff et al., 2010).

DOWNSTREAM RESPONSE TO IMPOSED FLOW TRANSFORMATION (DRIFT): Similar to the BBM and Holistic Approach, DRIFT focuses on the relationships between river water levels and the biophysical functions of species. The DRIFT method was developed in arid regions with water scarcity, ecological threats, and high social pressures. Monitoring outcomes and adjusting management plans are incorporated to establish an effective and comprehensive environmental flows program (King, 2003). Once discharge thresholds and associated biological consequences are identified, a minimum degradation level can be set (Tharme and King, 1998).

The accuracy of this method depends on scientific specialists predicting how flow variations will influence the function of social and ecosystem related components of concern (King, 2003). The DRIFT method is conducted through four modules:

1. **Biophysical module:** containing the river ecosystem description and potential consequences of flow changes. This module develops numerical estimates of river flow variables key to sustaining natural ecosystem function and survival of native riparian species.
2. **Socio-economic module:** incorporating links between current and future communities’ resources, livelihoods, and health under various river function scenarios. This module develops predictive capacity on how river change can influence quality of life for people economically or proprietarily tied to the river. This is typically done through the development of a computerized hydrologic simulation model capable of predicting impacts of alternative flow regimes.
3. **Scenario development module:** predicting how potential future flows can impact biophysical and socio-economic factors. After quantifying ecological and societal flow needs individually, incompatibilities are assessed, with special attention on spatial and temporal characteristics. Alternative management solutions are proposed collaboratively and tested through water management experiments to resolve and clarify critical uncertainties.
4. **Economic module:** listing compensation and mitigation costs associated with alternative scenarios.