REPORT FROM THE 2009 GILA SCIENCE FORUM

FROM THE SCIENCE PANEL:

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Executive Summary

The general purposes of the 2009 Gila Science Forum were to identify, discuss, and recommend (1) ways of determining the potential effects of flow modification on aquatic and riparian resources of the Gila River (including risks and uncertainty), and (2) how information gleaned from such efforts might be integrated to provide an ecosystem-based assessment of the effects. The science panel recognized the existing modifications to the upper Gila River ecosystem in New Mexico, but also noted that the system currently functions as a relatively natural ecosystem with a largely intact native fauna. The consensus of the panel was that flow modifications are likely to change the nature of this ecosystem, but those changes will depend on the location, timing, and magnitude of the modification. The natural complexity of the Gila River and its socio-economic context makes assessing the impacts of flow modification on aquatic and riparian resources inherently uncertain. However, integration of existing information from this system in combination with that from other similar systems and process based scientific understanding can be accomplished within context of a Systems Framework. Such a framework must also fundamentally integrate the diverse stakeholder values as well as specifications for the range of alternative flow modifications that are to be evaluated so as to yield an integrated socio-economic-ecosystem based assessment.

To assist in developing an integrated approach for decision making in this system, the panel recommends a Plan of Action that will assess the effects of flow modifications on the socio-economic-ecosystem within the Gila River Valley. The Plan of Action implements a Systems Framework to rank potential water-management policies in the Gila River watershed relative to how well alternative policies satisfy the diverse stakeholders' values (such as a sustainable socio-agro-ecosystem, possible future economic development, and maintenance of native biodiversity) within the bounds of existing legal constraints (such as water rights, agreements, and the Endangered Species Act). Within the framework, the best available science is used to form a flexible, adaptable, scientifically based, and transparent or "white box" conceptual model that links stakeholder values and legal constraints to water-management policies in the Gila watershed. Such a scientifically based conceptual model tailored to the Gila watershed and its stakeholders' values allows flow modification policies to be designed, evaluated, and ranked. The ranking then can be used by decision-makers to inform their choice.

The systems framework must be applied with full representation from across the set of stakeholders and in an iterative, or spiral, fashion such that each cycle of application identifies 1) the critical questions and stakeholder values, 2) uncertainties in the conceptual or computational model, and 3) data gaps that must be resolved in the next cycle. Analysis ends for practical purposes when policies can be clearly ranked in the face of uncertainties thus allowing decisions to be made that are robust to this uncertainty. However, by incorporating data obtained as chosen policies are implemented, further application of the spiral process can drive adaptive management of the Gila River watershed that could continue into the future with great benefit. A time frame is given for the first implementation year of the Plan of Action whereby two turns of the spiral process are completed.

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1. INTRODUCTION

1.1. Overview

The 2004 Arizona Water Settlements Act (AWSA) provides the potential for the state of New Mexico to develop additional Gila River water (up to 14,000 ac-ft yr^{-1}) as well as $66 million to $128 million in federal funds for projects related to water development. By 2014, New Mexico must give notice to the Secretary of the Interior how, or if, New Mexico wishes to utilize its benefits under the AWSA.

If the water is developed, it must occur under the conditions of the Consumptive Use and Forbearance Agreement (CUFA), a complex contract which defines the timing and amounts of Gila River water New Mexico can retain, in part based on stream flow and reservoir levels. Expenditures of funds must meet a water supply demand, and must be approved by the New Mexico Interstate Stream Commission in consultation with the Southwest New Mexico Water Planning Group.

The Governor of New Mexico has directed that responsible parties must use the best available science and information, coupled with a full and inclusive public involvement process, to protect the unique and valuable ecology of the Gila Basin and to provide for present and future water needs.

An important step in the decision-making process is to determine the potential effects of flow modification on the aquatic and riparian resources of the Gila River. The 2009 Gila Science Forum was designed to aid that process and was an extension of the 2006 Gila Science Forum (Dahm et al. 2006), which provided an overview of critical questions and information needs as well as broad recommendations for an integrated investigative framework to address these needs.

1.2. Purpose of the 2009 Science Forum

The general purposes of the 2009 Gila Science Forum were to identify, discuss, and recommend (1) ways of determining the potential effects of flow modification on aquatic and riparian resources of the Gila River (including risks and uncertainty), and (2) how information gleaned from such efforts might be integrated to provide an ecosystem-based assessment of the effects. Furthermore, the 2009 Gila Science Forum Planning Team developed four focal questions for the Forum and selected the six panelists with a breadth of expertise in the fields of hydrology, geomorphology, and ecology to provide input on those questions. The questions were as follows:

1. In broad and general terms, what are the potential effects of flow modification on the biological, hydrological, and geomorphological attributes of southwestern rivers?
2. What tools and methods are available to assess the biological, hydrological, and geomorphological responses of a river to human-induced flow modification? What are the advantages and disadvantages, risks and uncertainties associated with each tool and method?

3. How might information obtained from biological, hydrological, and geomorphological studies be best assimilated and integrated to understand the effects of flow modification on ecosystem function?
4. Recognizing that time and resources are limited (to about one year and $1 million), what are the most pressing tasks (including, potentially, filling information gaps) that we need to address in order to assess the effects of modified flows on aquatic resources of the Gila River?

1.3. Background

1.3.1 Gila River system

Geographically, the focus of the 2009 Gila Science Forum was the upper Gila River and associated riparian habitats in New Mexico from the confluence of Mogollon Creek downstream to the Arizona border (Figure 1). In this reach, the river flows through both broad alluvial valleys and narrow canyons. The Gila River originates in the Mogollon Rim of SE Arizona and SSW New Mexico. From its sources to mouth, it descends more than 9,750 ft in its 650 mile course (Gila River at Gila - elevation of 4,654 ft with drainage area of 1,864 square miles; Gila River near Verden below Blue Creek near the Arizona border - elevation of 3,203 ft with drainage area of 3,203 square miles). The East, Middle, and West forks join to form the Gila River in the Mogollon Mountains. The upper watershed is largely within the Gila National Forest. Downstream from Mogollon Creek, land use is a mix of private, state, and federal lands.

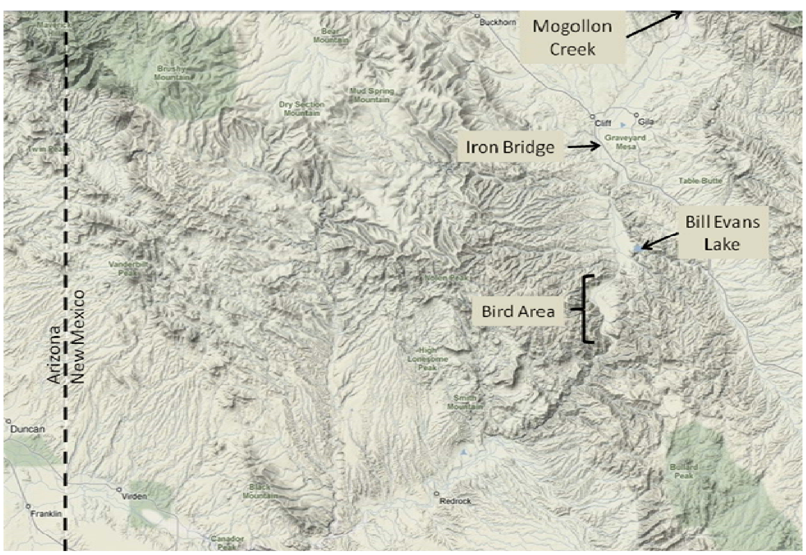

Figure 1. Topographic map of the Gila River between its confluence with Mogollon Creek and the Arizona-New Mexico border.

Agricultural uses of the alluvial valley include irrigated crops and livestock grazing. From its origins to the Arizona line, the Gila River is free-flowing with the exception of several irrigation diversions and a pumping station that delivers water to Bill Evans Lake (Figure 1).

Long-term monitoring of the fish assemblages demonstrates a strong link between stream discharge and the ecology of the stream (Propst et al. 2008). Eight species of native fish are currently present in this region. Populations of two federally listed species, loach minnow (*Tiaroga cobitis*) and spikedace (*Meda fulgida)* have persisted in the system, but their occurrence among six study sites (including one below the Iron Bridge) has varied considerably. In addition, the riparian forest communities include a diverse bird assemblage including the federally listed southwestern willow flycatcher (*Empidonax trailii extimus*) and the yellow-billed cuckoo (*Coccyzus americanus*), which is a federal candidate status species.

1.3.2 Water-resource management

Management of freshwater resources often results in conflicts between ecosystem and human needs, particularly in arid regions such as southwestern U.S. Recently, Poff et al. (2003) outlined an alternative model for conducting river science that is relevant to the Gila-Cliff river valley. Their approach emphasizes partnerships between scientists and stakeholders, and the importance of conducting scientific experiments at scales that are relevant to resource management. They suggest a first step is to review large-scale river experiments on existing and planned water-management projects and then to engage the problem through a collaborative process involving scientists, managers, and other stakeholders. A goal is to integrate case-specific contextual knowledge into broader scientific understanding.

Effective management of any watershed resource requires an initial inventory of the available water and the distribution of that water, as fluxes, within the watershed. A common method to assess the water resource of a watershed, and to estimate the amounts of water that may be available for human use and to support ecosystem services, is the development of a water budget. As a start to constructing the conceptual model that is proposed herein, a water budget is considered to be an essential foundation. A water budget is an estimated accounting of the water volumes entering, leaving, and stored on and beneath an area, typically a watershed or drainage basin, during a specified period. At the watershed scale, an ecosystem area is the same as the hydrologic area in which it functions. In equation form, a water budget for a drainage basin or watershed is:

$$P = O + ET - I + \Delta S \tag{1}$$

in which P is precipitation, generally as an average depth or volume per year, O is outflow as streamflow (mean discharge), ET is average loss of water per year as combined evaporation and transpiration, I is inflow of water, generally as streamflow and runoff into a channel reach, and ΔS, which can be either positive or negative, is the average change in stored water per unit time interval, generally of groundwater, soil moisture, and imposed additions or extractions for a specified number of years. In simplest form, a water budget identifies the average volume of water supplied to an area and ecosystem as precipitation, and the ways by which components of the volume are distributed as biophysical processes.

For the purpose of presenting a detailed conceptual model that may be applicable to the upper Gila River Basin, basic components of a water budget are summarized for natural water fluxes in the upper part of Figure 2. Precipitation (mostly highly variable amounts of rain and snow) falls on the watershed and, especially for semiarid areas, much of it is returned to the atmosphere as evapotranspiration. Lesser amounts result in streamflow and inflow to a specified area or reach of the watershed. Variations in the amount of streamflow and inflow may cause changes through time in the water stored as soil moisture and groundwater, and result also in additional evapotranspiration.

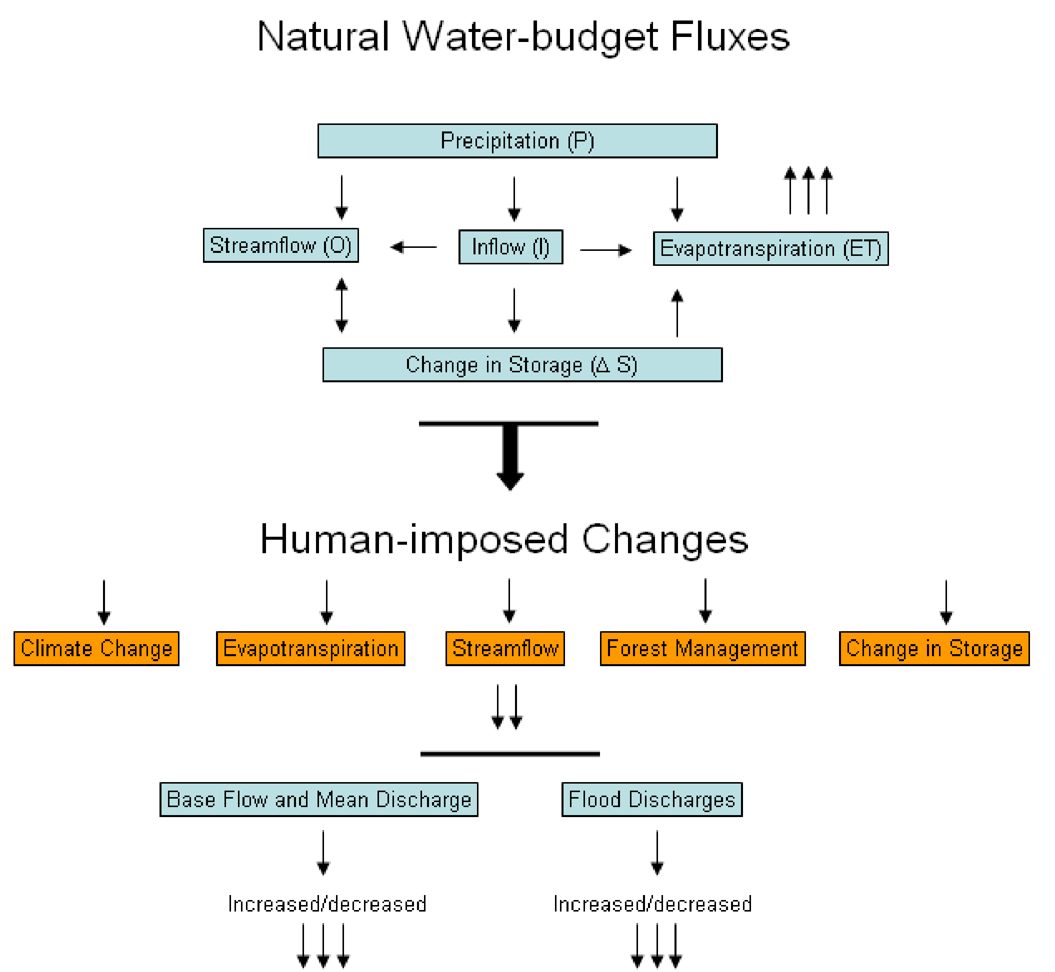

Figure 2. Water budget Fluxes as a combination of Natural and Human Imposed changes.

If the natural fluxes of water are altered by climate change and/or, human actions, such as streamflow additions or abstractions, or forest management, all components of the water budget may be affected, and the complexity of the model may increase dramatically owing to interactions among the water-budget components. In Figure 2, streamflow is selected as an example of the effects of human modifications on a drainage network. Depending on the amounts of imposed flow increase or decrease, base flow and mean flow may be increased or decreased, and discharges of floods also may be modified – possibly for all floods but perhaps only for those floods with return periods of 10 years or more.

More specifically, during drought or seasonal dry periods, daily discharge of the Gila River at Gila, NM, can diminish to around 0.6 $m^3 s^{-1}$ (20 $ft^3 s^{-1}$) (lower 10th percentile) and the river approaches having intermittent discharge. In consequence, if low flows are decreased further due to water withdrawals, and as a result of lowering the amount of groundwater stored in the alluvial aquifer, parts of the upper Gila River likely will have more sustained periods of intermittent discharge. Other possible effects could be channel incision, seasonal elimination of aquatic biota owing to reduced availability of water, opportunities for replacement of some native plants by invasive species, altered water chemistry and temperature, a lowered zone of saturation (water table) in the alluvial aquifer leading to the elimination of some flood-plain and terrace plants, and reduced replenishment of fine-grained channel sediment (see also section 2.1, below). If low flows are increased, discharge at base flow will be increased and the river may become fully perennial.

If the frequency and magnitude of flood discharges are reduced, especially of the higher-magnitude floods, effects to bottomland processes could be reduction in channel and riparian-zone sediment replenishment, loss of channel complexity and riparian-zone habitat, reduction of native species diversity, and increased potential for replacement of native vegetation by invasive species. If flood discharges are unchanged, sediment-sorting processes (such as for the maintenance of riffles and gravel bars) are likely to be continued, aquatic-habitat complexity will be maintained, and ecosystem stability may remain high. An increase in flood discharges probably would increase deposition on flood-plain areas of overbank sediment, nutrients, organic matter, and seeds, but also could cause an increase in flood damage and bank erosion.

Once an accounting has been made of the water resource and of the direct consequences of modification of that resource, more detailed conceptual models of how changes in water fluxes may affect ecosystems, human needs, and human objectives can be constructed. In addition, feedbacks among geomorphic, hydrologic and ecosystem processes can be incorporated. All of this would be predicated upon a basic qualitative understanding of the system.

Extending the largely physical fluxes of a water budget, Bunn and Arthington (2002) presented a more specific model of how flow modification may influence the ecology of river systems. Their model describes the consequences of altered flow regimes for aquatic systems (Fig. 3) and highlights the importance of high flows in maintaining habitat complexity of stream channels and both lateral (i.e., along the stream channel) and longitudinal (with the riparian zone) connectivity of the system. Moreover, Bunn and Arthington (2002) emphasized how different species (including differences between native and non-natives) respond to different aspects of the flow regime. For example, high flows may initiate spawning of native fishes, whereas low flows may initiate spawning of non-native fishes (Propst and Gido 2004). In general, altered flow regimes result in a reduction in aquatic biodiversity (Bunn and Arthington 2002, Xenopoulos and Lodge 2006). However, a more refined assessment of how specific aspects of flow regimes (e.g., timing of flows, magnitude of peak flows, flood or drought duration, etc.) affect biodiversity are not well known and likely to differ depending on ecological traits of species and other systems-specific factors.

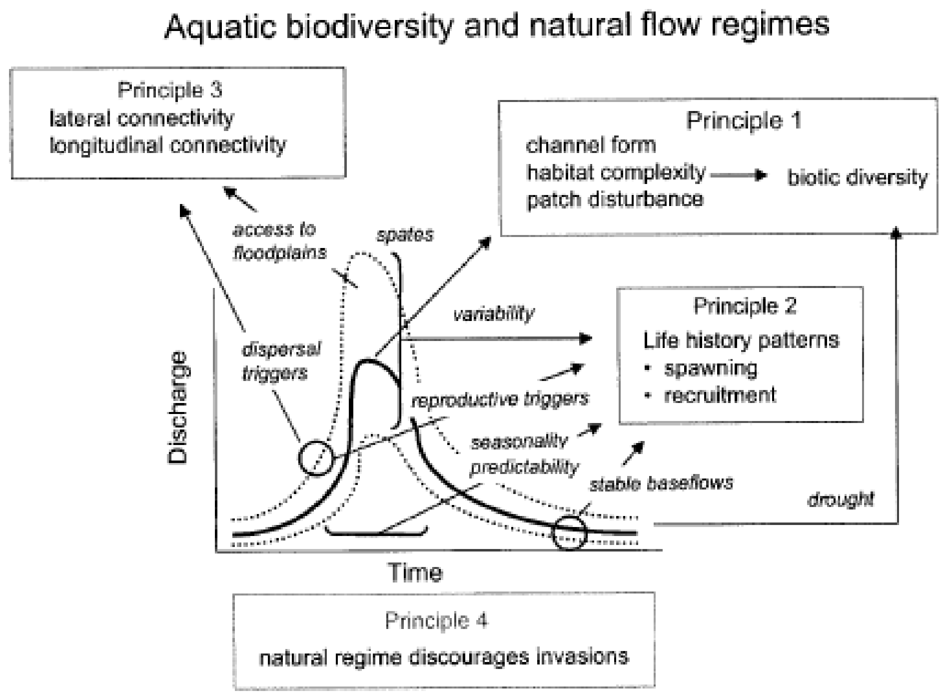

Figure 3. Conceptual model describing the relationship between flow regimes and aquatic biodiversity (from Bunn and Arthington 2002).

2. QUESTIONS OF THE FORUM: SUMMARY OF IMPORTANT CONSENSUS POINTS

The 2009 Gila Science Forum Planning Team requested that the panelists provide answers to four basic questions over the course of the Forum. Answers to the questions varied among the six panelists; below, we have briefly summarized answers to each question across the group. The panel also answered questions presented to the moderator from the audience (Appendix A). Running notes from the Forum that include more detailed answers to the four basic questions and to questions from the audience are contained in Appendix B.

2.1. Question 1

In broad and general terms, what are the potential effects of flow modification on the biological, hydrological, and geomorphological attributes of southwestern rivers?

Potential effects of flow modification include, but are not limited to, increase or decrease in stream discharge, current velocity, channel depth and width, habitat complexity, temperature, sediment size and transport (including both bedload and suspended components), channel aggradation or degradation, change in richness and diversity of biotic elements (instream and riparian systems, plant, invertebrate and vertebrate lifeforms), changes in behavioral, functional, energetic, and life history characters of biota, changes in relationships between and among biological, chemical, and physical components of the system, and changes in suitability of the system to benefit some biota and disadvantage others. The bottom line is that the potential effects of flow modification are many and varied, and that, other than the obvious potential benefits to human users, are generally regarded as negative or adverse for the co-evolved system itself. For example, there is a consensus among studies that modifications of natural flows are often detrimental to native fishes (e.g. Xenopoulus and Lodge 2006). These adverse effects of flows on native fish biota have been related to: (1) fragmentation of habitats, (2) reduced baseflow, (3) altered habitat area and channel form, (4) modification of basal resource, and (5) enhancement of nonnative species. Finally, it must be recognized that changes in the Gila River system have already been induced by previous and ongoing flow modifications, changes in land cover and land use, and the introduction of nonnative species. Additional flow modifications must be assessed in the face of current alterations, and should include analyses of cumulative effects.

Changes in flow modifications will affect the connectivity (alternatively, fragmentation) of the Gila River, its riparian ecosystems, and its subwatersheds (tributaries). In the lower Colorado River system (of which the Gila River is a part), native fish species with historically fragmented spatial distributions have exhibited relatively high frequencies of local extinction (Fagan et al., 2002; 2005). To gain an understanding of how flow changes might affect spatial distributions and habitat, it seems necessary to relate the fluxes of water and sediment to the characteristics of the stream network, and to view all bottomland features, including the stream channels and riparian-zone surfaces, as results of those fluxes. Furthermore, if the water flux of the Gila River (discharge) is modified (reduced), the water available for downstream fluvial processes and ecosystem services will be reduced by the amount of the reduction. Such changes underlie the need for an explicitly spatial perspective on flow modifications as discussed below.

2.2. Question 2

What tools and methods are available to assess the biological, hydrological, and geomorphological responses of a river to human-induced flow modification? What are the advantages and disadvantages, risks and uncertainties associated with each tool and method?

There are no predictive tools or methods to assess reliably and quantitatively the biological responses of flow modification ahead of time. Some inference can be gained from assessing other river systems that have undergone similar flow modifications, but fundamental differences among river systems, particularly in arid and semiarid regions, often preclude suitable deduction. The only reliable assessment comes from comparing what are believed to be the most important variables before and after the modification over a timeframe that captures decadal changes in the system, especially as related to geomorphic changes and the establishment of non-native fauna and flora. The key advantage of a before-and-after approach is its direct application to the site of impact and at the time of impact. Disadvantages include lack of control system(s), absence of any opportunity for replication, inability to account for natural variation (which may be extreme), and, most importantly, the institutional inability to modify flow alterations once projects are developed if system changes are deemed unacceptable. Specific tools for pre- and post-project evaluations to assess hydrologic, geomorphic, and biological responses are best evaluated when specific flow-modification projects are proposed because the potential effects of such projects vary considerably.

Among the many tools and methods available to assess the potential impacts of flow modifications on the Gila River system are a wide range of quantitative modeling approaches, the most basic of which is the development of an integrated strategy for evaluating aquatic and bottomland ecosystems. These approaches range from simple statistical models and “off-the-shelf” computational packages (with standard biological and physical submodels) to an integrative systems-based model that would be developed specifically for the Gila River system. Regardless of the approach, the model chosen should be 1) applicable to different types of rehabilitation, 2) supported rigorously by empirical studies, 3) appropriate to different spatial and temporal scales, 4) focused on the hydrologic processes that underpin biological conditions, and 5) capable of leading to an understanding of current conditions, extent of change, and reasons for perceived ecosystem decline.

2.3. Question 3

How might information obtained from biological, hydrological, and geomorphological studies be best assimilated and integrated to understand the effects of flow modification on ecosystem function?

Given the potential complexity and scope of flow modifications that might be considered, it seems necessary to develop an integrative modeling framework customized specifically for the upper Gila River Basin. The framework should be a basis for addressing the stated purposes of the 2009 Gila Science Forum: to understand how flow modifications may affect the aquatic and riparian-zone resources of the Gila River, and to use that understanding as a means of constructing an ecosystem-based assessment, or conceptual model, of the effects. The framework must be transparent. Attributes of the approach must include public recognition, political backing, important elements of the system (ecological, social and economic), important values (aspirations), and post-project assessment. Also, the framework must identify and effectively include the hydrologic, geomorphic, and biological processes. This assimilation must take place within a spatially explicit model that recognizes the hierarchical structure of stream systems (Frissell et al. 1986) so as to permit an evaluation of alternative flow-modification scenarios tied to specific river reaches. Spatially explicit structure also allows for the linking of information from small to large scales. Explicit modeling of the interdependence of system components (e.g., how fish are influenced by vegetation, geomorphology, volume of flow, non-native fishes) forces integration of information across specific domains to be precise. Such transparent integration is not possible with off-the-shelf models. Spatially explicit interdependent models can take various forms including multivariate statistical models to examine how measured variables interact and respond to one another and or more process-based models including both direct and indirect mechanisms. This approach to synthesis requires a team of individuals possessing a diversity of expertise to implement and integrate the model and associated analyses.

2.4. Question 4

Recognizing that time and resources are limited (to about one year and $1 million), what are the most pressing tasks (including, potentially, filling information gaps) that we need to address in order to assess the effects of modified flows on aquatic resources of Gila River?

Given constraints of time and resources, and because field data collected from a single year are not likely to yield informative results, it would be advantageous to spend the time and resources available to develop an integrative model that links large-scale physical-habitat processes with biological processes such as population dynamics. Thus, the model should have a design that rests on the recognition that a stress, in this case flow modification, applied to a site of a stream will ultimately affect all physical and biological processes throughout the drainage basin. In the context of developing and parameterizing that model, it would be appropriate to determine how bottomland features and therefore habitat are affected, what the "best known" species and ecosystem services are, and how available empirical data collected to characterize these species and services can be compiled in a useful manner. Spending time and resources on this particular issue is advantageous because it directly addresses what has been a weak link in water resources management, namely the interplay between physical and biological processes (Anderson et al. 2006).

A phased approach is suggested with the first year designed to complete a synthesis of existing knowledge of the system and develop a conceptual framework for the Gila River. The first phase will be most effectively approached if the proposed projects, including the nature, timing, location, and mechanism of flow modifications, are defined specifically such that potential modifications can be integrated explicitly into the model framework. Subsequent phases would be used to collect additional data and conduct suitable analyses. A recommended approach is to convene a “think tank” of experts on flow effects from each relevant discipline to help design studies to fill data gaps and to provide input into the overall model framework for assessing effects of flow modification.

3. A RECOMMENDED PLAN OF ACTION

The panel unanimously recommends a Plan of Action implementing a Systems Framework that makes use of a thorough water-budget analysis linked to the natural and human induced functioning of the socio-agro-ecosystem to rank an inventory of water-management polices or projects for the Gila River watershed relative to diverse stakeholder values and within the confines of legal constraints. The recommendation of this Plan of Action was not taken lightly. The panel believes the breadth of stakeholder values combined with legal constraints necessitate an inclusive and transparent process facilitated through this implementation. This recommendation is consistent with recommendations from the 2006 Science Forum (Dahm et al. 2006).

The breadth of stakeholder values was revealed by supporting documents for the Science Forum and by attendees at the Forum. These values include (but are not limited to): benefits directly related to new water-development projects, current water use, preservation of lifestyles and landscapes in the river valley, relatively high water quality, three federally listed species that inhabit the river (spikedace, loach minnow) and associated riparian zone (southwestern willow flycatcher), other species of concern, naturally functioning semiarid river ecosystem, longitudinal and lateral connectivity within the river ecosystem, and aesthetics. The need to assess flow alternatives relative to such diverse stakeholder values means that conventional, piecemeal approaches to the problem will be unworkable. Instead, the diverse values need to be placed in a common framework that is compatible with multiple currencies during evaluation, necessitating an integrative modeling approach that links values with possible flow modifications through important and interdependent physical, biological, social and economic processes.

The assessment of flow alternatives also must be placed within the context of current regulatory constraints, most prevalent of which are the AWSA, CUFA, Endangered Species Act (ESA), National Environmental Policy Act (NEPA), and Clean Water Act (CWA). The first two constrain the types and design of water projects, whereas the latter three limit the range of allowable effects of water development on environmental values. ESA limits effects on populations of listed species and alterations to critical habitat. NEPA will ensure evaluation of other environmental resources at local, regional and global scales and will include assessments of the cumulative effects of proposed projects. CWA regulates water quality and has provisions to ensure no net loss of wetlands. ESA may require appropriate reasonable and prudent alternatives to mitigate adverse effects on listed species, whereas NEPA and CWA may indicate mitigation measures to compensate for adverse effects. The integrative approach proposed by the panel is designed to include these regulatory restrictions and allow for effective and simultaneous consideration of important stakeholder values.

3.1. Goals and Approach for Recommended Plan of Action

The goal of our recommended Plan of Action is to create the ability to rank potential water-management policies or projects in the upper Gila River watershed relative to how well the alternatives would satisfy varying stakeholders' values (such as a sustainable socio-agro-ecosystem, possible future economic development, and maintenance of native biodiversity) while achieving legal constraints (such as water rights, agreements, and the Endangered Species Act). To achieve this goal a Systems Framework should be used within which a flexible, adaptable, scientifically based, transparent or “white box” conceptual model is implemented that links stakeholder values and legal constraints to water-management policies in the Gila River watershed. The conceptual model then allows policies or projects pertaining to flow modification to be designed, evaluated, and ranked in the face of uncertainty. Such a ranking then can be used to inform decision-makers.

The systems framework must be applied with full representation from across the set of stakeholders in an iterative, or spiral, fashion such that each cycle of application identifies 1) the critical questions and stakeholder values, 2) uncertainties in the conceptual or computational model, and 3) data gaps that must be resolved in the next cycle (Figure 4).

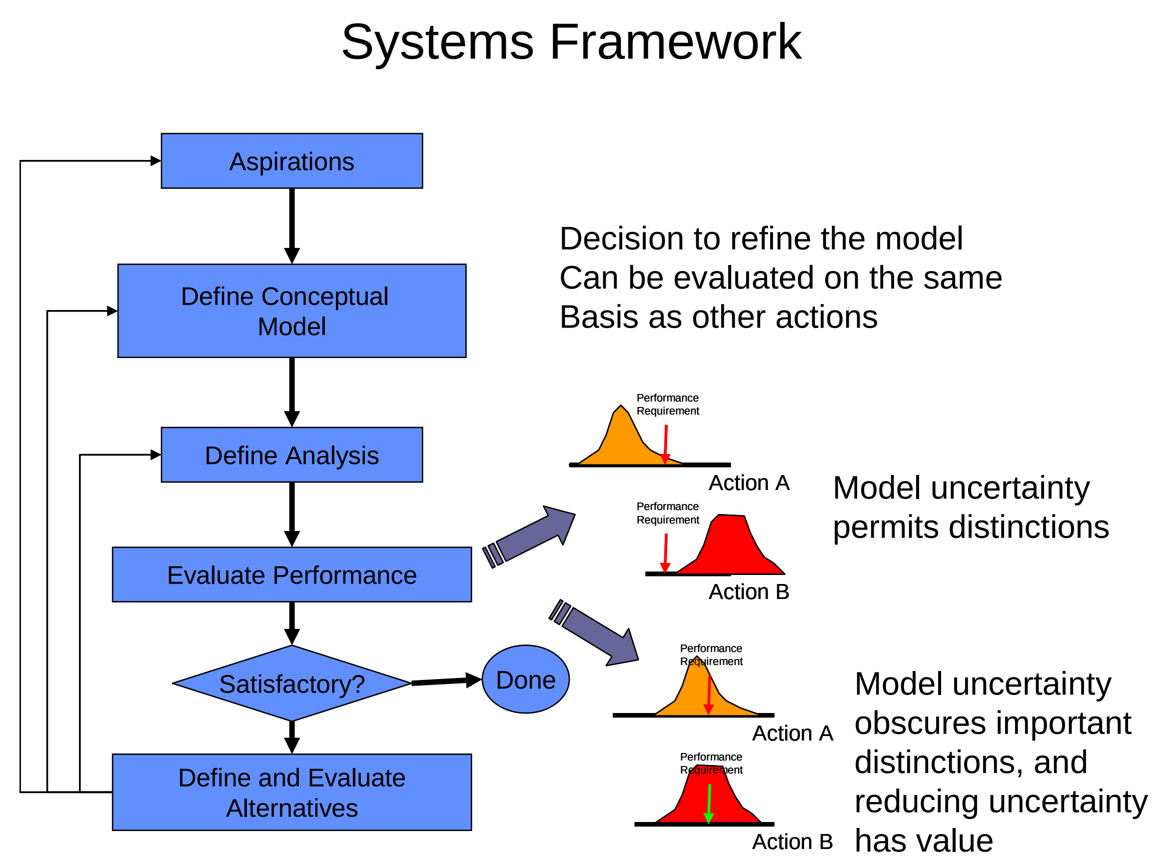

Figure 4. Graphical schematic for ‘spiral development’ of a systems-modeling approach to decision-making in the face of diverse stakeholder values and model uncertainty.

Analysis ends for practical purposes when policies can be clearly ranked in the face of uncertainties thus allowing decisions to be made that are robust to this uncertainty. However, the process may be continued indefinitely to adaptively manage the system as policies are implemented, stakeholder values change and the system evolves. In the first year, it is expected that two turns of the spiral process cycle would be accomplished. Below we present each of these steps in greater detail.

3.1.1. Aspiration

The overall Aspiration is to find an acceptable balance within the set of stakeholder values that also meets various legal constraints. The stakeholder values with regard to different resources within the Gila River watershed must be clearly stated before the systems framework can be applied. It must be recognized that the relative values within the set may change in time and new stakeholder values may need to be included in the future.

3.1.2. Conceptual Model

The conceptual model links the critical stakeholder values that characterize the system's attributes to the policies that may be used to balance these values while fulfilling legal constraints (Figure 5). These policies are the flow modifications that are to be considered.

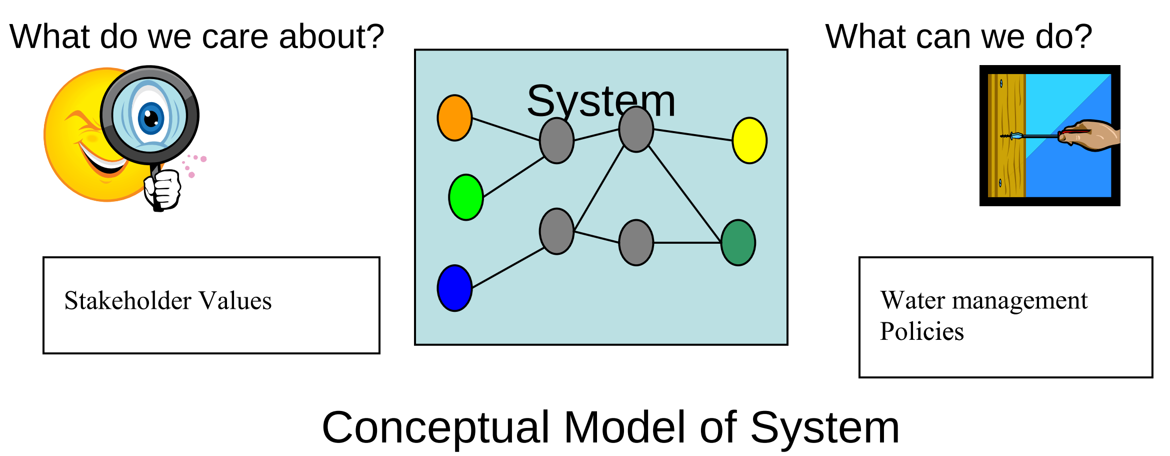

Figure 5. Graphical overview of the contents and purposes of a systems-level conceptual model.

To build a defensible basis for connecting policies to values, one needs to identify the critical components of the socio-agro-hydro-ecosystem and identify the linkages among those components. Conceptually, the model can be defined as a network of components (such as the local agricultural community, riparian habitat, at-risk aquatic species, and downstream water users, each represented conceptually by a gray ellipse in Figure 5) that are linked through their influences on one another (such as through the transfer of water, sediment or nutrients).

An example of a starting point for building this conceptual model is provided in Figure 6 from the Decadal Plan for the Long Term Ecological Research Network (USLTER 2007). This figure illustrates a systems-level approach for integrating ecological science with socioeconomic considerations. The ecological and socioeconomic components involve very different currencies and units of measure, but can be linked and examined as a system via the types of linkages and feedbacks that exist among the components. We note that hydrologic components are conspicuously absent from Figure 6 and they and other components of importance to a conceptual model for the Gila River watershed must be incorporated.

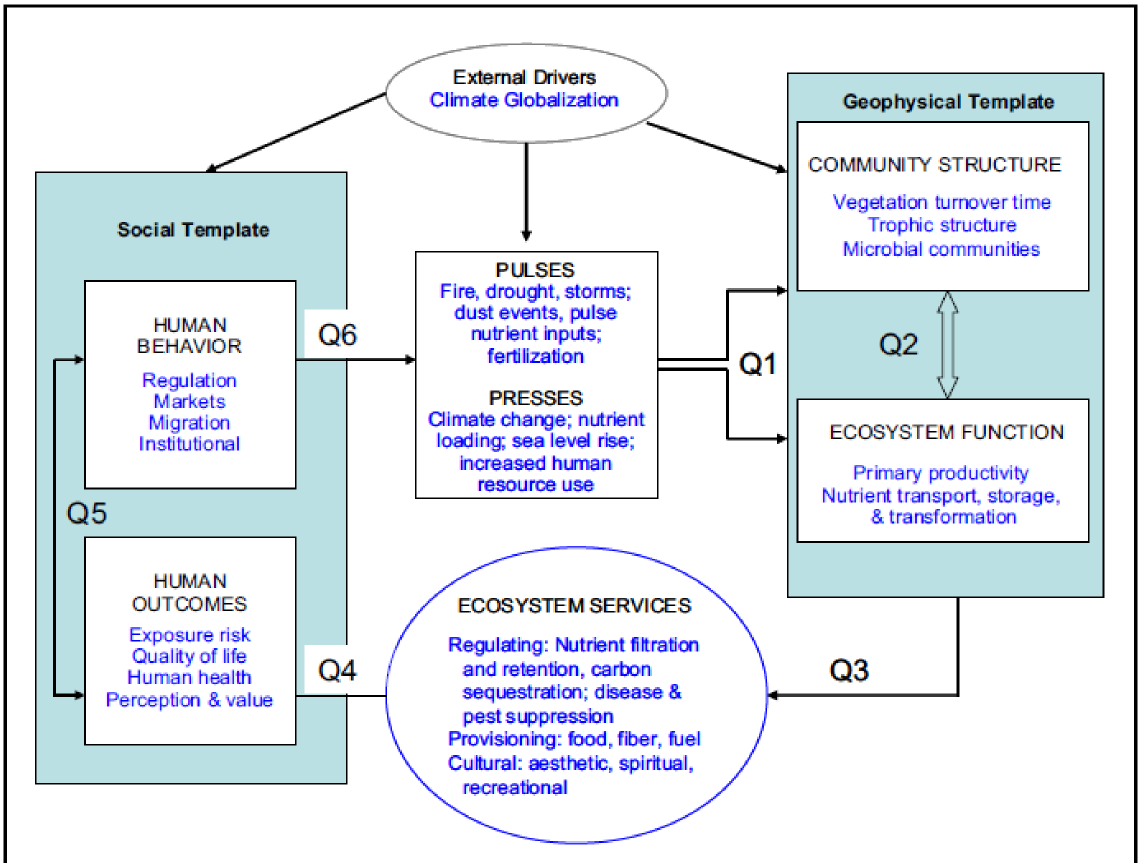

Figure 6. The schematic above details a framework for addressing network-level research questions adapted from Figure 3.2 of the Integrated Research Plan of the US Long Term Ecological Research program (USLTER 2007). The right-hand side represents the domain of traditional ecological research; the left-hand side represents human dimensions of environmental change; the two are linked by the services provided by ecosystems (at bottom), and by pulse and press disturbance influenced or caused by human behavior (at top). Q1-Q6 refer to integrating questions presented elsewhere in USLTER (2007); these can be specific to particular applications.

Each component in the conceptual model can be resolved to greater or lesser degree depending on the policy that is being evaluated and the requirements to reduce uncertainty in its ranking. The building of a more highly resolved component should be accomplished with full participation of stakeholders; the model that is built must be both scientifically based and owned by the stakeholders. An example of a more highly resolved conceptual model that focuses primarily on the hydrologic component and the use of water within the Gila River watershed is shown in Figure 7. This model was built through participation of a range of stakeholders within the region.

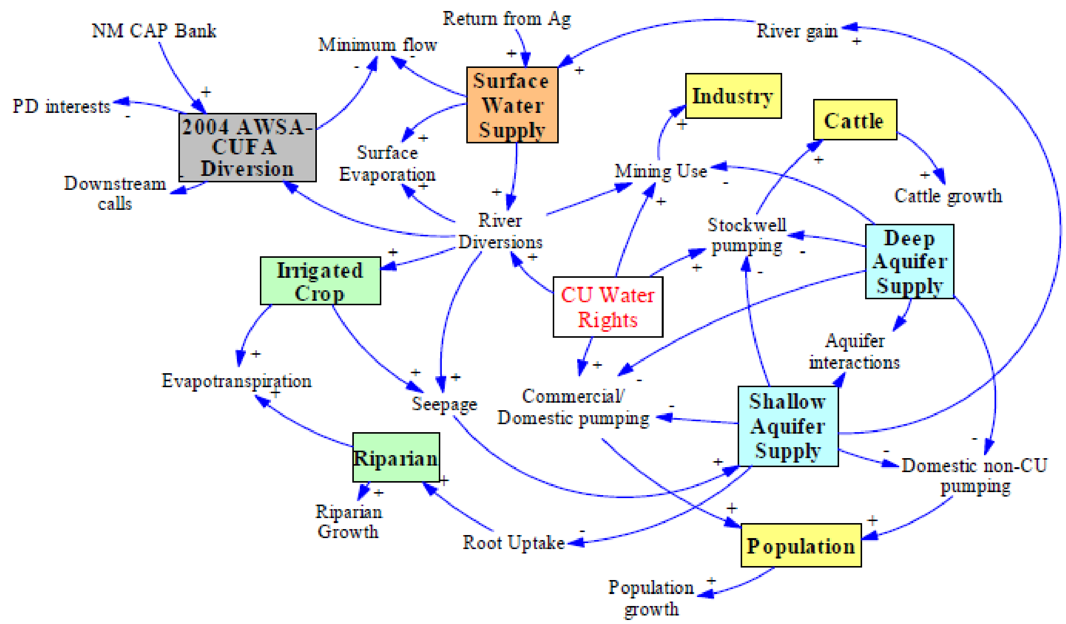

Figure 7. An example of a higher resolution conceptual model for the hydrologic component focusing primarily on extractive water use. This model has been constructed with a range of stakeholders to explore the interplay between water extraction and diverse stakeholder values in the Gila River watershed (Sun et al. 2008).

Once the conceptual model has been defined, it can be implemented computationally for policy evaluation through a variety of computational approaches that may include decision tree analysis, linear programming, discrete event analysis, systems dynamics, or agent-based models. The model of Sun et al. (2008) depicted in Figure 7 was implemented using a systems dynamics approach in a commercial software package. Making the model accessible over the web in an interactive form so that stakeholders can use it to manipulate parameters, test their preconceived understanding of the system, and explore tradeoffs among stakeholder values would be an excellent step that could help build public confidence in the process.

3.1.3. Analysis

After a thorough computational exploration of the model, policies for water management can be ranked by balancing tradeoffs between stakeholder values (these are modifiable and can be changed through the spiral application process) while also satisfying regulatory and system constraints. As part of the analysis process, the ranking of a given policy choice is evaluated for robustness in the face of uncertainties due to how the system is represented in the model and due to the magnitudes of particular parameters. To accomplish this analysis, the conceptual model must be as parsimonious as possible with the smallest number of parameters intrinsic to its behavior that still represent the system with scientific credibility. Additionally, the model will need to be implemented in a computational environment designed for executing and analyzing the large number of individual simulations likely required (tens of millions). An example of one such study is an investigation of community-level strategies for influenza pandemic mitigation (Davey et al 2008).

3.1.4. Evaluation

In each cycle of the spiral application process, uncertainty in the ranking of alternative policies is used to identify those refinements to the data, model, conceptual framework, and suite of aspirations required for the next cycle. Inability to distinguish a given policy's rank focuses subsequent efforts and begins another cycle of application. This spiral development process can end when uncertainties have been resolved sufficiently enough to identify the top set of policy options to choose between. Or the process can continue with refinement, novel inputs, or new data as these become available in context of the continued and ongoing adaptive management of the watershed.

3.2. Timeline

The goal should be to push through two cycles of the spiral application process within the allotted year. In this way, the implementation of the systems framework will be developed, modified as needed and integrated within the culture of decision-making for water management of the Gila River watershed. The process by which this will be accomplished must be fully open, transparent, and inclusive of diverse stakeholders. A reasonable sequence of events is:

Step 1) Start with as full a set as possible of stakeholder values, legal constraints and possible water management policies. These would be defined before the start of the modeling effort and conceptualized during this first step. (month 1)

Step 2) Configure the overall preliminary conceptual model that connects stakeholder values to water management policies. (month 1)

Step 3) Refine sub-components of overall model in critical areas as needed. Make use of as much available information as can be assimilated during the period including both process-level understanding and specific data from the Gila or other similar watersheds. Examples of specific types of information for hydrologic and ecosystem components that could be needed for an appropriate socio-economic-ecosystem conceptual model is listed in **Table 1**. (months 2-3)

Step 4) Define and accomplish analysis that considers a matrix of policy options for a baseline set of model parameters, evaluates the ability of the system to simultaneously satisfy diverse stakeholder values, and ranks the policy options based on that ability. Repeat the analysis for a range of alternatives that include model uncertainty and parameter uncertainty. Evaluate the analyses with regard to the ability to rank policies robustly with respect to this uncertainty. (months 4-5)

Step 5) Evaluate the sufficiency of the analysis. (month 6)

Step 6) Repeat steps 1-5. Include additional data as necessary. (months 7 through 12)

The implementation of each of these steps will involve workshops and meetings so that stakeholders and their values are comprehensively represented as are scientists and social scientists, system engineers, and agencies. The initial process we envision would involve three teams, one comprised of stakeholders to provide general guidance, oversight, and input, a second comprised of domain experts who would advise the development of the conceptual model, and a third systems team that would implement the systems framework including the construction of the computational model and its analysis. Membership in the stakeholder team should be open and available to any entity or individual that chooses to participate, including but not limited to state and federal agencies, local governments, water developers, environmental groups and other non-governmental organizations, and private citizens. The stakeholder team would provide inputs as requested to support the domain experts and system team's activities. The expert team would be comprised of individuals with the necessary diversity of experience and skills, including but not limited to hydrology, geomorphology, and aquatic ecology. The primary technical effort would be accomplished by the systems team where systems engineering and analysis expertise is required that spans conceptual model development, computational implementation, analysis definition and performance evaluation to develop and implement the system's framework described above.

While we have called out three individual teams, the boundaries of each must be blended to allow active collaboration across team. Once established, the team of three must work together intrinsically to accomplish overall group goals. To accomplish this intrinsic across team collaboration, we recommend a half-to-full time coordinator whose time is dedicated to and focused on the goal of establishing an integrated systems framework to rank alternative water management policies. To ensure continuity the coordinator should be an individual with substantial institutional tenure and commitment to water resource management within the state of New Mexico. Annual or semi-annual public meetings would provide a forum to involve and inform a greater breadth of local and regional community interests.

We have outlined the first year of our recommended Plan of Action, however, we emphasize that implementation and use of the systems framework necessitates a multi-year effort whose long-term success will require dedicated funding and institutionalized management that will keep the model up-to-date and properly functioning as changes are made, stakeholders values shift and new data are incorporated. Outcomes from the first year should be used to determine specific elements for subsequent phase(s), such as detailed studies and additional analyses to assess effects of flow modifications. Long term monitoring of variables indicative of system health can be used in context of the systems framework to implement adaptive management through time and provide new data to support further model adjustments and refinement of model results.

3.3. Summary of what the Plan of Action would yield

In summary, the panel recommends a Plan of Action that integrates stakeholder values and legal constraints to select water management policies now in context of the 2004 Arizona Water Settlements Act and in the future via adaptive management of the Gila River watershed. Within context of a systems framework, the spiral development of a systems-level model for integrating hydrologic, geomorphic and ecological science with socioeconomic considerations would yield a ranking of alternative, candidate scenarios for flow modifications within the Gila River in terms of their impacts on water availability, abilities to satisfy diverse stakeholders' values, and acceptability within legal constraints. Importantly, the plan would take advantage of the participation and input of a diversity of stakeholders representing an equally diverse suite of interests, and ultimately yield a result that addresses the expectations of all. In general, this approach is not able to provide an assessment of the merits of alternative scenarios on an absolute scale (e.g., Option A is 3 times better than Option B), but instead provides information about the relative (i.e., ranked) merits of the options (e.g., Option A ranks above Option B). In this way, many detailed date requirements may be avoided and only added if the ranking of options can not be resolved. However, we emphasize that details on the location, timing, nature, and magnitude of flow modifications will likely be essential.

Table 1 Examples of specific types of information for hydrologic and ecosystem components that could be needed for appropriate socio-economic-ecosystem conceptual model	
1	Amounts and variability of precipitation as indicated by records from weather stations in and near the upper Gila River Basin
2	Amounts and variability of streamflow as indicated by discharge records from USGS gage sites along the river; much of this information has already been compiled and summarized by Mike Harvey in his consultant's report.
3	Documentation of the present sites where perennial discharge typically changes to intermittent or ephemeral discharge; the documentation should include where those sites have been in the past to provide an indication of change through time.
4	Estimates of ground-water extractions based on the number of known wells and typical pumping of those wells.
5	Present and recent land-use practices
6	Inputs and outputs of organic matter
7	Primary and Secondary productivity
8	Changes in community structure (i.e., types and abundances of species)
9	Changes in species interactions (i.e., competition, predator-prey relations)
10	Spatial distribution of habitats
11	Changes in connectivity of habitats

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APPENDIX A: AUDIENCE QUESTIONS ARISING DURING THE GILA SCIENCE FORUM

Audience questions from June 3, 2009. Questions are given in alphabetical order and are presented verbatim except for small changes to improve clarity.

During discussion of stakeholder Question 1.

Appears system functioning quasi-naturally and is retaining fair portion of native fauna, but several species lost – razorback, CO pikeminnow, and Gila topminnow – why were they extirpated and not others? How will flow modification affect invasion potential and success of nonnative fishes?

Aren't there potential biological benefits of flow modification, i.e. augmentation of low flows?

As examples, smallmouth bass to 22" and Sonora sucker to 24"+ have been taken from the upper Gila – these are near-record sizes. What does this tell us about the fertility of the stream? And, how might flow modification affect this fertility?

Aside from the obvious positive effects of flow modifications (withdrawals) to humans, are there any positive effects to other resources, or are they all negative?

Basin hydrology – what is the baseline? (1) How much modification of peak flows? (2) How much modification of base flows? i.e. Need a discussion of existing hydrology -surface and elsewhere.

(1) Can the variability/dynamics flows/connectivity of the Gila be maintained or artificially recreated under damming, diversion or other modification? (2) Can the panelists speak more on how the resiliency of the system can be maintained under diversions of water? (3) Can we pre-determine how much flow can be decreased before a phase shot will occur?

Climate prediction question: At the Economic Forum last week, the climate speaker concurred with Dr. Glass about expecting lower flows based on snowpack. However, he said that monsoon effects are unpredictable and could increase or decrease. So, couldn't there be as much or more precipitation and flow, just with a different timing?

Connectivity, East Fork Gila. Studies indicate that elimination of predators, beaver and increased cattle grazing have encouraged salt cedar and significant reduction in cottonwood. The channel-floodplain geomorphology channel also. Your comment?

Could you explain how the presence of non-native fishes might interact with flow modification to affect native populations?

Do flood events help bring in new populations of species previously scarce in a particular reach of river? Or do they tend to weaken diversity of species?

Do we have any knowledge of what would be the critical break point for threatened species regarding hydrological modifications (flow modifications)?

Do you see a benefit of storing water at peak flow to use to restore water during drought? Plus for species, ecology and populations.

Does the panel agree that connectivity and species viability would be enhanced if base flows could be augmented during dry periods?

Does the state now know the amount of water claimed in NM in the upper Gila and more importantly do they know the actual use vs. the amount claimed? (Are there plans to obtain this information?)

Exactly who are the Gila stakeholders group? How have the panelists been chosen?

General comment: The planning timeframe is 2050. Could panelists please keep this timeframe in mind when disusing effects or conclusions for all 4 questions? (Other sideboards needed for productive discussion?)

Has the aquifer been mapped? What is the relation I-flow to the aquifer?

Have there been successful mitigation measures/programs to flow modifications for threatened and/or endangered species? Please provide examples.

How has historic modifications affected data used for flow and species representation. How does overabundance of vegetation and meandering of the waterway affect species and flow. Water temperature affect species representation.

How is threshold of acceptable effect identified and quantified? Once a native fish assemblage in downward spiral as consequence of enviro (human-caused) modification, can it be reversed and how?

How resilient can a river system in the Southwest be given the stability (quasi-stability) appears to be hinged on high variability – including high highs and low lows? Diversions and dams, according to international studies, always result in a NET LOSS.

How would flow modification effect hydrology of plant species and groundwater recharge on which human species rely?

How would you characterize the potential taking of 14,000 acre feet from the Gila? A very major flow modification; or a minor modification? An order of magnitude!

If the 14,000 acre-feet are taken primarily from high flows, what are the main effects to consider/mitigate?

If a diversion on the Gila River removes water only during peak flows or floods what would be effects on aquatic/riparian community? At a time when dams are being removed at various places across the U.S. and other places as a way to restore ecosystem function why are these flow modifications being planned for the Gila or even thought of?

Is there a recent characterization of the geomorphology of the river at and between both gages, including bed particle size distribution (D90, D50, D84) and is it considered important to conduct this after low, average, and at high flow events.

Isn't it a folly to realistically think that you can maintain the biodiversity of the Gila while at the same time extracting more H2O than is already being removed? Isn't this already shown across SW? (Note: there are 2 wishes of Gov. Richardson)

Middle Fork – overgrazing. Please expand on human activity's impact. Some observers would re-categorize "disperse cattle grazing" to overgrazing.

Re: land use to increase water flow. However, past and current (NMSU, Univ AZ Forest Sec) research has show that this is not successful in pinyon-juniper. If it were successful, then one would think that the vast vegetational treatments across the Gila National Forest to restore fire-adapted ecosystems would be showing significant effects on flow. Comments?

Ron Ryel spoke of mitigating modifications of flow. Can he and others discuss what specific mitigations could be instilled to make up for the loss of $H2O$? (are there really any?)

What are the general (e.g. layman terms) impacts of removing peak flows on the river in both broad alluvial and canyon sections of the river from the upper gage to the state line? (short term impacts?) (long-term impacts?)

What is the status of understanding of groundwater in the Gila/Cliff alley (and down to the state line) including location, age, connectivity/importance to surface flow of the river? [Are there any recent studies?]

What methodology would you recommend to correlate stream flow changes with the rise and fall of ground water levels in the adjacent riparian plant community?

Worst case scenario: As we heard in the forum last week – Due to global warming we may lose our snowpack in 50 yrs. Possibly there will be frequent years with little if any snow. If this happens what is the impact on the Gila species and ecology?

You have adequately described potential effects of flow modification on connectivity, but what are other effects, e.g., to temperature, sediment, transport, stability, etc.?

During discussion of stakeholder Question 2.

Address the results of worldwide studies that conclude: reservoirs and diversions have always damaged they system more than it has helped – (over the short and long term)

Are there data that could be collected regardless of future scenarios? What are they? (e.g. to characterize the current state of the river [and its watershed])

Can each of you name one river system in the west – or even other arid systems – that has retained its biological integrity after a human induced modification? (ergo withdrawal)

Do we have any modeling/data on effects on the ecology of similar rivers that flow or hydrological changes produce? What can we learn from these to help us develop our model for the Gila?

Have past data been assembled including aerial photos and what future/current efforts should be carried out immediately such as LIDAR? (Basic data for understanding the rivers' past changes during the period of record – assuming BOR or defense photos go back to at least the 1940s or earlier)

How can we resist the temptation to support a flow-modification in order to test our models? To resist what Openheimer called "the technical sweetness" of the knowledge we would gain from before and after studies even if there were deleterious effects of modification?

How do you determine the appropriate time to move from a conceptual model to a process based model?

How do you determine what tools and methods to use when you have a great diversity of interests with an even greater variation of expected outcomes?

If it is true that small floods (<1000 cfs) occur much more frequently than large floods, and that small floods would be relatively more affected by a diversion, could you please describe what we do know about the ecological role of small floods in the Gila River system, particularly in a valley-reach like the Cliff-Gila where the occurrence of off-channel wetlands becomes an emergent property.

If the riparian and riverine ecosystems of the Gila are governed, in large part, by the catastrophic ecology of periodic large-scaled flooding events, what does that mean in terms of planning for those stochastic events so that you have an ecological community in place that can successfully absorb those energies so that a valley reach like the Cliff-Gila works as a release valve?

In modeling the Free Flow alternative how can it be precise without a great deal of historic information?

Is it true that a predictive model is useless unless it has been tested and validated?

Once potential effects id'ed, what are specific tools that could be used to quantify, for example, flow decrease causes species x to decline. What is effect on larval fish assemblage. How is this measured?

Sometimes the selection of correct input data is important to model use. What are good "estimating methods" to help select good and correct input data?

“The nature of the flow modifications determines the effects.” Explain – with emphasis on river diversions during flood stage.

Uncertainty is a certainty. Can you use an engineering “safety factor” approach to accommodate uncertainty and avoid paralysis?

Uncertainty is a constant but how do you deal with it – can you use the engineering approach that lumps uncertainty in a factor of safety?

We’ve talked a lot about models. What process is used to build/populate these models with information? Do you use just published literature? Do you consult with experts and researchers who work in the area? Do you hold facilitated meetings to work through the process of building the framework/model or models? Do consultants build this/these, or can it be a collaborative process?

What analysis can be done to look at the risk of a reservoir system on allowing establishment of invasive species that will seriously impact downstream irrigators vs. the risk under other scenarios including diversions and no change to the river as it currently runs? e.g. zebra mussel quagga mussel and algae that drastically effects water quality like in the Klamath reservoirs

What are the biggest holes in data/relationships that we need to collect to build models?

What is the record/experience in looking at actual impacts to what may have been predicted by models/methodologies?

We have been discussing results of “flow modification” throughout the forum. What flow modification are you referring to? Be specific please.

You have mentioned a lack of understanding of the system. Given the lack of data on many parts of the system, outside of fish, what would you load into a model to even be able to use a model? (i.e., - herps, birds, mammals, plants)

During discussion of stakeholder Question 3.

A more important question, if we assume we have the know how to integrate biology, hydrology and geomorphology with a well thought out approach is how do you assimilate and integrate socio-economic and public interest information?

As scientific experts and based on your past experiences, when do you think it is appropriate to finally propose an action? (i.e. – diversion dam). – Or – can an effects analysis be done without that known?

At the 2006 science forum all but one of the 6 scientists participating agreed that there is great scientific value in leaving some rivers undammed and unsiphoned so that there is a model to study in river restoration (the 6th scientist recused himself). How should that value be weighted in the decisions about flow modification?

Can you use sensitivity analysis to bracket potential outcomes of diversions?

If you were given a concrete flow modification scenario tomorrow how long would it take to develop a high confidence effects model for the yellow-billed cuckoo or spikedace?

In New Mexico, how much diversion <for irrigation purposes or otherwise> of the Gila River goes on today? How does current diversion compare to historical such diversions?

Isn't the whole process of developing a model inappropriate unless there are plans to test and validate the model prior to undertaking the action (withdrawal)? Therefore, the utility of a predictive model is unknown unless tested and validated!

Relative Bob Glass slide on interdependency model. What are the aspirations at this point? a) identified? c) consensus? c) diversity?

The session has focused on flow modification effects on aquatic species. What about the effects on aquatic species if the Gila remains a largely free-flowing stream?

We are talking about river flow modifications as if it is going to happen. Why aren't we talking more about no flow modification and what won't happen – the Rio Grande River from Elephant Butte Lake south into Texas.

You use the term "ecosystem" yet not once have the panelists talked of the aquifer, groundwater, or inflow except fleetingly – why?

During discussion of stakeholder Question 4.

Beyond a single species approach, what are more "creative" (Paul Marsh) approaches to studying effects of altered flows?

Conclusions based on current data will be only as good as the data you have. You suggest data is sufficient on 2 fish and 1 bird. However, they're 3 spp. Of 1000's. How confident then can I be as a land manager in your results as being useful for my decision process?

Do you see benefits in multiple experts and disciplines working together (to assess effects of flow modification) vs. paying consultants to provide data?

Gila River hydrograph info has been portrayed in the presentations, the foyer, and the handouts. How does this compare to the 2 (two) gages on the San Francisco River?

Given that one scenario for the AWSA water is to divert flood flows over 300 cfs, what are the potential ecological effects of reduced flood magnitude? How would one approach this issue scientifically?

How do you build into process and criteria ability to reverse course if outcomes not what originally desired?

If flow is a master variable in aquatic ecology and if high river flows are important for sediment and nutrient routing, and rejuvenation of habitats, does taking water under the CUFA only at high flows potentially impair the system more than spreading the diversions out to a variety of flows?

If the 14,000 a-f withdrawal is on high flows only, could the panel identify key attributes that might be affected? Is it channel maintenance and pool scour? Is it overbank flow and riparian vegetation? Is it NOT some attributes that would not change?

In the 2006 science forum, conclusions included the following. Does this panel agree? Anything new? (1) The process needs to include ecological, cultural and economic assets. (2) Integrate science : flow shape the : habitat, systems, biology and species connectivity. Changing flow favors non-indigenous species. Consider human effects. (3) Engage stakeholders.

It was my understanding that the scientific studies of the Gila River would inform the choice of which diversion (if any) would be least deleterious on the river we all love and depend on. What I heard today was that the scientists can't study or predict the effects of flow modification until after a particular project is chosen. This is a conundrum, no? Can you help?

The scientific methods and socio-political funding rarely coincide fully. What three studies would you begin first?

There seems to be a presumption that any hydrologic/geomorphic change will always cause adverse biological change. (1) How elastic are the biological systems? (2) Have existing hydro-physical modifications already exceeded the elasticity of the biological system?

What background information do the panelists have about the AWSA, stakeholder status, and Gila Basin activities? E.g., Decision making structure and committees? Desired conditions in progress? Sandia lab model in progress? Watershed treatments across broad landscapes (up to 100,000 ac/yr) to restore fire adapted ecosystems that are out of balance? If they have some knowledge, could they address some of these efforts specifically (vs. theoretically)? Where are we on the right track?

Why are endangered species more important than people – the citizens of this country?

APPENDIX B: FORUM NOTES